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LECTURES

ON

POLARIZED LIGHT,

1

DELIVERED BEFORE

THE PHARMACEUTICAL SOCIETY OF
GREAT BRITAIN;

AND IN THE

MEDICAL SCHOOL OF THE LONDON HOSPITAL.

Jonathan [illegible]

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TO

CHARLES WOODWARD, ESQ., F.R.S.,

PRESIDENT OF THE ISLINGTON LITERARY & SCIENTIFIC SOCIETY,

THIS WORK,

ON A SUBJECT WITH WHICH HE IS INTIMATELY ACQUAINTED,

IS INSCRIBED,

AS A TESTIMONY OF RESPECT AND ESTEEM,

BY HIS SINCERE FRIEND,

THE AUTHOR.

PREFACE.

The following Lectures were delivered in the spring of 1843, before the Members of the **Pharmaceutical Society of Great Britain**, and are now in course of publication in the *Pharmaceutical Journal.* The substance of them has formed, for some years past, a portion of the Annual Course on Chemistry, delivered in the **Medical School** of the London Hospital.

To the undermentioned eminent philosophers the author has been principally indebted for the information contained in the following pages:

Sir Isaac Newton.—Opticks; or, a Treatise of the Reflections, Refractions, Inflections, and Colours of Light.

Dr. Thomas Young.—A Course of Lectures on Natural Philosophy and the Mechanical Arts.

Sir D. Brewster.—Various papers in the Transactions of the Royal Societies of London and Edinburgh. Also two numbers on the Double Refraction and Polarization of Light, published under the superintendence of the Society for the Diffusion of Useful Knowledge. Likewise, a Treatise on Optics, in Lardner's Cyclopædia, and the article "Optics" in the Encyclopædia Britannica, 7th edition.

Fresnel.—Elementary View of the Undulatory Theory of Light, in the Quarterly Journal of Science for 1827, 1828, 1829, translated and annotated by Dr. Thomas Young. Also various papers in the Annales de Chimie et de Physique. Likewise, Extrait du Bulletin de la Société Philomatique, Décembre, 1822, and Fevrier, 1823.

Sir J. Herschel.—Article "Light," in the Encyclopædia Metropolitana. Also, Transactions of the Cambridge Philosophical Society, and Philosophical Transactions.

Biot.—Various papers in the Mémoires de l'Academie Royale des Sciences, and in the Annales de Chimie et de Physique.

Airy.—Mathematical Tracts. 2d edit. 1831. Also, Transactions of the Cambridge Philosophical Society.

Pouillet.—Elémens de Physique Expérimentale et de Météorologiè, 2 vols. 1827.

Peclet.—Traité Elémentaire de Physique. 2^me. ed. 2 vols. 1830.

Quetelet. — Notes to the French Translation of Herschel's Article on Light. Also, Positions de Physique. 1834.

Lloyd, Rev. H.—Report on the Progress and Present State of Physical Optics, in the Report of the Fourth Meeting of the British Association. 1835. Also, Lectures on the Wave Theory of Light. 1841.

Powell, Rev. Professor.—Elementary Treatise on Experimental and Mathematical Optics. 1833. Also, a General and Elementary View of the Undulatory Theory, as applied to the Dispersion of Light. 1841. Likewise, various papers in the Philosophical Magazine.

Rose, Gustav. — Elemente der Krystallographie. 2^te. Aufl. 1838. (A French translation of the 1st edition of this work).

Dove.—On the Circular Polarization of Light: translated in Taylor's Scientific Memoirs, vol. i.

Soubeiran.—Journal de Pharmacie. 1842.

Ventzke.—Annals of Chemistry. December, 1842.

The author takes this opportunity of offering his warmest thanks to his friend, Mr. Woodward, for his valuable assistance and advice on many occasions, in the performance of experiments on Polarized Light; as well as for the loan of various pieces of apparatus, contrived and adapted by Mr. Woodward, for the public illustration of the phenomena of Polarized Light.

To Mr. Darker, optician and manufacturer of polarizing apparatus, of Paradise Street, Lambeth, the thanks of the author are also justly due, for his disinterested zeal, skill, and attention in promoting the objects of the author in the preparation of the present course of Lectures.

J. P.

47, FINSBURY SQUARE,
September, 1843.

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ON

THE POLARIZATION OF LIGHT,

&c. &c. &c.

LECTURE I.

WITH the concurrence of the Council of your Society, I have undertaken to deliver three lectures on the Phenomena of Polarized Light. I have done so, because I believe that their singularity, variety, splendor, and useful applicability will create great and universal interest in the minds of my auditors, whatever be their pursuits, occupations, or acquirements.

I am acquainted with no branch of experimental philosophy capable of presenting such brilliant and gorgeous phenomena, and which are so well adapted for illustration in the lecture-room, as polarized light. In its power of unfolding to our view the intimate structure and constitution of natural bodies, it certainly has no superior, if indeed it have any equal. It furnishes us with characters for recognizing and distinguishing many bodies, and it gives us the means of determining the nature of the changes going on in some of the recondite operations of nature. It is a subject whose phenomena are so complicated and intricate, that it not only admits of, but actually requires, the highest departments of mathematics to elucidate them; and it is, therefore, very properly placed in the very first rank of the physico-mathematical sciences.

But in all societies and associations, the lovers of knowledge are of two kinds, philosophers and utilitarians. The first pursue science for its own sake, the second for its usefulness. With the latter every step they take in the acquirement of knowledge is accompanied with the question "*cui bono?*" With such, all scientific researches which have no immediately practical bearing, which, according to their narrow views, cannot be at once shown to be *useful*, are neglected, perhaps even sneered at. Though with such I profess to hold no community of feeling; yet as I am desirous of combining in these lectures, the *utile* with the *dulce*, I think I can venture to hold out to them ample remuneration for the time they may devote to the study of polarized light, by attending these lectures.

If I can show them that this agent furnishes us with a more intimate knowledge of the nature and properties of those substances, by the commerce in which most of the Members of this Society gain their bread; if I can demonstrate its applicability to the detection of adulteration of foods, drugs, and chemicals; if I can point out its application to the determination of the commercial value of saccharine juices; if I show how it has been applied to determine the nature of the changes which occur in certain chemical and vital processes, in which ordinary chemical analysis completely fails us; if I prove that it may aid members of my own profession in detecting the existence of certain diseases; and, lastly, if we show the possibility of its use to the mariner in aiding him, under certain circumstances, to avoid shoals and rocks—I trust even the utilitarians will admit that the study of polarized light is both advantageous and profitable, and that the time of this Society has not been unprofitably occupied by these lectures.

These are only a portion of the valuable and practical uses of which polarized light is susceptible. Its phenomena are so intricate, and at present so little understood by the public, that a very large number of persons, who might otherwise perhaps beneficially avail themselves of its services, are ignorant alike of its powers and of its uses. We may, therefore, hope that when it becomes better known it will be found more extensively useful.

Common and polarized light agree in several of their leading properties, and though these lectures are intended to illustrate the peculiarities of polarized light, yet before we can prove what is peculiar to the one, we must be acquainted with the general properties of the other, and thus, I conceive, I must introduce polarized light to your notice, by *a preliminary general view of the physical properties of light.*

Moreover, the phenomena of polarized light are so numerous, various, and intricate, that the student is very apt to become bewildered with an immense multitude of facts, and to forget, if indeed he ever knew, the conditions which are requisite for the production of each phenomenon. Hence, then, it becomes desirable that we should give him some artificial aid to assist in the conception of facts, and the modes of observing them; as well as to show him how these manifold phenomena are mutually connected and dependent. We require in fact some means of generalization. Such will be found, I think, in the *undulatory hypothesis of light.*

I propose, therefore, to occupy this lecture with a brief statement and demonstration of the properties of light, and to take a hasty glance at the hypothesis of waves or undulations; so that I trust you will leave this room to-night with some general notions of the possible physical causes of common and polarized light, and almost anticipate some of the statements which I shall have to make in the next lecture.

1. GENERAL STATEMENT OF THE PHYSICAL PROPERTIES OF LIGHT.

1. *Propagation of Light.*—Light emanates from luminous bodies with the enormous rapidity of above 190,000 miles per second. This has been ascertained in two ways; first, by observation of the times at which the eclipses of the satellites of Jupiter are perceived by us at different seasons, according to the part of its orbit which the earth happens to be in; and, secondly, by the phenomenon called the aberration of the fixed stars. The first method gives 192,500—the second, 191,515—miles per second.

2. *Variation of Intensity.*—The intensity of light decreases as the square of the distance increases. At twice the distance, it has only $\frac{1}{4}$ of the intensity, at thrice the distance $\frac{1}{9}$ the intensity, at four times the distance $\frac{1}{16}$ of the intensity, and so on.

The reason of this is, that being highly expansile, it illuminates four times the space at twice the distance, nine times at thrice, and sixteen times at four times the distance; hence, its intensity must be inversely as the square of the distance.

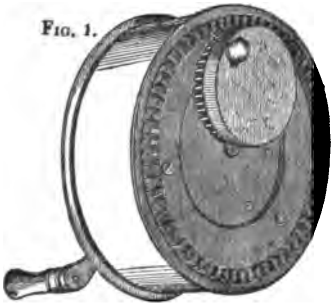
The law is aptly illustrated by a quadrangular pyramid of wood, divided horizontally at equal distances, into four parts or segments of equal height. The upper segment has a square base, whose area we shall call 1. The second segment has also a square base, but its area is 4. The area of the square base of the third segment is 9, and that of the lowest or fourth segment, 16. Here the distances of the bases of the segments from the apex of the pyramid, are as 1, 2, 3, 4, while the areas of these bases are as 1, 4, 9, 16.

The readiest demonstration of the law for the lecture-room, is the following:—Let the light from a lantern pass out through a square aperture, and be received on a semi-transparent screen, on which square spaces are marked. Notice at what distance the beam of light illuminates one of these squares. At double the distance, it will illuminate 4, at treble 9, at quadruple 16 squares.

In *Photometry*, we avail ourselves of this law. If two luminous bodies, at unequal distances, produce the same amount of illumination, the relative quantities of light evolved by these bodies, are as the squares of the distances. Thus, if a lamp, at four feet distance, give as much light as a candle at one foot, the lamp actually evolves 16 times as much light as the candle. Count Rumford's photometrical process of observing at what distances two lights gave two shadows of equal intensities, as well as the photometers of the late Mr. Ritchie and of Professor Wheatstone, are on this principle. But all these modes of measuring light are objectionable, since they are based on the imperfect and varying judgment of the eye.

Professor Wheatstone's recently-constructed photometer is a very ingenious contrivance. It is a cylindrical box, of about two inches diameter, and one inch in depth, and which contains a system of two wheels and pinions. On the face of the box, and near to its external border, is a circle of cogs. In the centre of the face is an axis, to which is attached an horizontal arm, carrying a toothed wheel or disk, the teeth of which fit into the cogs of the outer circle. This wheel has a double motion, it rotates on its own axis, and also revolves within the cogged circle. To this disk is attached a small, hollow, glass bead, silvered internally, and which moves with great rapidity backwards and forwards across the face of the cylinder. The motion is communicated by turning the handle on the opposite face of the box. If this photometer be placed between two lights, and the bead put in rapid motion, we observe two parallel luminous lines, about the $\frac{1}{10}$ of an inch apart. By adjusting the relative distances of the two lights from the photometer, so that the brightness of the luminous lines may be equalized as determined by the eye, and then squaring the distances, their comparative intensity may be ascertained[*].

FIG. 1.



Wheatstone's Photometer.

3. *Transparency and Opacity.*—Some bodies allow light to penetrate them, as air, water, glass, crystal, &c. These are called *transparent* bodies. Others, however, refuse to give passage to light, as the metals. The latter are termed *opake* bodies. But some substances, which in the mass are opake, become transparent when reduced to thin films. Gold is an instance of this: in the lump it is opake, but as gold leaf it allows light to traverse it.

4. *Reflection.*—When a beam of light falls on a smooth-polished surface, a portion of it is *reflected.* The incident and the reflected ray make each the same angle with the reflecting surface, hence the law of reflection is, that *the angles of incidence and reflexion are equal.* This law holds good under all circumstances, whether the reflector be plain or curved.

A polished metallic plate as a *speculum* is a good reflector. *Glass*, being transparent, reflects both from its anterior and posterior surface. Hence in some optical experiments, where it is desirable to avoid the confusion from a double reflexion, the posterior surface of the glass is either ground, or blackened by means of soot, candle-smoke, or size and lamp-black. This proceeding is especially desirable in experiments on polarized light. *Silvered glass*, that is, glass covered on the posterior surface by an amalgam of tin, as the common looking-glass, is not adapted for accurate optical experiments, on account of the reflection from the metal as well as from the glass.

---

[*] This instrument is made by Messrs. Watkins and Hill, of Charing Cross.

5. *Refraction.*—When a ray of light passes obliquely out of one medium into another of a different density or combustibility, it changes its direction, or is bent out of its course; in optical language it is *refracted.* If the second medium be denser, or more combustible than the first, the refraction is *towards* the perpendicular; but if the density or combustibility of the second medium is less than that of the first, the refraction is *from* the perpendicular.

If the ray fall perpendicularly on the refracting surface, it suffers no change in its direction, in other words, it undergoes no refraction.

In most optical instruments in which refracting media are required, *glass* is employed, as in the camera obscura, astronomical and terrestrial telescopes, microscopes, magic lanterns, common spectacles, eye-glasses, &c. The oxyhydrogen apparatus, which I shall use in these lectures for illustrating the phenomena of polarized light, serves, when deprived of its polarizing part, for use as a microscope (*oxyhydrogen* or *gas microscope*) the images of the objects being thrown on a screen. Used in this form, it is simply a refracting instrument. Its structure I shall hereafter explain. *Quartz* or *rock crystal* is used, under the name of *Brazil pebble*, as a refracting medium for spectacles, on account of its greater hardness, and its being less liable to scratch. The *diamond* and other precious gems have been occasionally used for microscopic lenses. Jewellers employ a *glass globe filled with water*, to concentrate the rays from the lamp which they use to work by. The water is generally coloured pale blue, to counteract the reddish yellow tint of the artificial light. *Amber*, when cut and polished, is sometimes used for spectacles. When the object is to concentrate rays of light, and to exclude those of heat, lenses of *alum* or *sulphate of copper* may be employed.

I have already stated, that the law of reflection, as regards the direction of the reflected ray, is the same for all reflecting media. But the law of refraction is very different, each refracting medium having its own peculiar action on light.

A variety of curious and well-known phenomena result from the unequal refracting powers of different bodies, or of the same body in different states of density. Thus the apparent crookedness of a stick placed obliquely in water; the difficulty of hitting a body, as a fish, in water, when we take an oblique aim; the deception experienced in estimating the depth of water, except when viewed perpendicularly; and the altered position of a body (as a piece of money) contained in a basin, when viewed obliquely, first when the basin contains no water, and afterwards when water has been put in—these, and many other phenomena, result from the greater refractive powers of water than of air, and the consequent change of direction which the luminous rays suffer when passing from one medium to the other. Again, the tremulous motions of bodies, when viewed through an ascending current of heated air, and by which an excise-officer is said to have, on one occasion, discovered a subterranean still in the Highlands of Scotland, result from the unequal refracting power of air in different states of density.

6. *Dispersion.*—If a ray of white light be made to traverse a refracting medium, or, in other words, to suffer refraction, it is found to have undergone a remarkable change—it is no longer perfectly white, but more or less coloured. It is assumed, therefore, that white light is made up of coloured lights, and that these, being unequally refrangible, are separated, or, in optical language, are *dispersed.* In this way, seven colours are obtained, viz. *violet, indigo, blue, green, yellow, orange,* and *red.* These are usually procured by a triangular piece of glass, called a *prism*—the seven colours constituting the *prismatic* or *solar spectrum.* This mode of producing colours from white light is called the *decomposition*, the *analysis*, or the *dispersion* of light. If we allow the oxyhydrogen lime-light to pass out of the lantern through a slit, and receive it on a prism, the spectrum may be thrown on the cieling of the lecture-room, or on the screen before us.

To persons unacquainted with philosophical investigations, few facts seem more astonishing, and even improbable, than that of *white* light being compounded of differently *coloured* lights. I shall, therefore, dwell for a few minutes on this topic.

Every one is familiar with the fact, that, by mixture, colours are altered. Thus blue and yellow form *green;* red and yellow form *orange;* while blue, with different proportions of red, yields *indigo* or *violet.*

You will, therefore, readily believe, that of the seven prismatic colours into which the prism decomposes white light, three only may be primitive, and four compounded.

Primitives.	*Compounds.*
Red	Orange
Yellow	Green
Blue	Indigo
	Violet

If the seven prismatic colours be rudely printed on a circular disk of card, and then be made to rotate rapidly, the union of these colours on the retina gives us an impression of greyish-white.

If we paint the three supposed primitive colours, viz., red, yellow, and blue on a similar disk, and cause this to revolve, we also obtain an impression of greyish white.

These experiments, therefore, favour the notion that the sensation of white light depends on the simultaneous impression of differently-coloured lights on the retina; and, secondly, that three of the prismatic colours being capable of giving the sensation of white light, they probably are the primitive colours, the others being compounds. Hence, white light is called *compound* or *heterogeneous light;* while the three colours, red, yellow, and blue, are termed *simple* or *homogeneous lights.* Each of these may be termed a *monochromatic light.* Orange, green, indigo, and violet, on the other hand, are *mixed colours.*

It follows, from this view of the subject, that two colours (one of which must be a *mixed* colour) may by their union or mixture produce white light. Colours or tints which do this are called *complementary.*

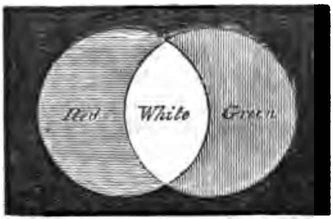
Complementary Tints.

Red...	and	Green.
Yellow	"	Indigo.
Blue...	"	Orange.

White and *black* are also said to be complementary.

I shall now proceed to demonstrate the accuracy of these positions. If I throw two beams of coloured light, one red, the other green, on a screen, we see two circular disks of coloured light, and by making them overlap, they produce white light. A similar result (that is, the formation of white light) is also produced by the overlapping respectively of disks of indigo and yellow, and of blue and orange. These colours are obtained by a complicated process. The oxy-hydrogen lime-light is refracted by the *condensers* in this lantern — then polarized — then doubly refracted or depolarized by a thin film of selenite—then refracted by the two *powers*—then analysed by a double refracting prism.

Fig. 2.



Formation of White Light.

By this process, the nature of which will be fully explained hereafter, we have destroyed the yellow and the blue, leaving the *red,* of one beam—while the red only has been destroyed in the other beam, leaving the *yellow* and the *blue* (which by their mixture constitute *green*). If we then cross the two beams, the red and the green by their mixture form white light.

The position of the orange or green lights in the spectrum favours the notion of their being mixed colours; since the orange is placed between the red and the yellow, and the green between the yellow and the blue.

But the indigo and the violet being placed the most remote from the red, appear to present an obstacle to this notion. Dr. Brewster, who adopts the supposition of there being three primitive colours, supposes that the solar spectrum consists of three spectra of equal lengths, a red, a yellow, and a blue one; and that the position of the maximum intensities of these colours varies, while certain portions of each of the three colours form white light, by mixing with the other colours in the requisite proportions—the excess of colour giving the predominating tint to that part of the spectrum where it exists. Thus in the red part of the spectrum, there is an excess of red rays, in the yellow part of yellow rays, in the blue part of blue rays, in the violet part of both blue and red rays.

This view of the subject has never appeared to me satisfactory; and accordingly another and a more probable one presenting itself, I am inclined to adopt it, more especially as it is supported by some experiments recently made by Sir John Herschel*. Suppose a repetition of the primitive colours of the Newtonian spectrum; the red of the second spectrum being partially superposed on the blue of the first spectrum. The extreme blue rays of the first spectrum being intermixed with the red rays of the second spectrum, will give the sensation of indigo and violet. But it may be asked, where are the other colours of the second spectrum? The reply is, that they are not visible to the eye. What evidence, then, it will be said, is there of the existence of invisible rays beyond the first or Newtonian spectrum? The evidence is twofold—first, the well-known chemical effects produced beyond the visible spectrum; and, secondly, Sir John Herschel's experiments before referred to. In his first paper†, in which he announces the extension of the visible prismatic spectrum, and the existence of a new prismatic colour beyond the violet; he states, that this colour appeared to his eyes as well as to those of a friend, to be lavender-grey. But in a more recent paper‡, he appears to have satisfied himself that the colour is yellow. "And if such," he adds, "rather than lavender or dove colour, should be the true colorific character of these rays, we might almost be led to believe (from the evident reappearance of redness mingled with blue in the violet rays) in a repetition of the primary tints in their order,

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[*] This notion was thrown out by Professor Grove, in his Lectures on Light, delivered at the London Institution, in November, 1842.

[†] *Philosophical Transactions*, for 1840, p. 19.

[‡] *Ibid*, for 1842, pp. 195, 196.

beyond the Newtonian spectrum, and that if, by any concentration, rays still farther advanced in the chemical spectrum could be made to affect the eye with a sense of light and colour, that colour would be green, blue, &c., according to the augmented refrangibility."

The following diagram serves to illustrate this view:

	Primitive Colours.	*Mixed Colours.*
Newtonian Spectrum	RED	
		ORANGE.
	YELLOW	
		GREEN.
	BLUE	
		INDIGO.
		VIOLET.
Hypothetical Spectrum	Red	
		Orange.
	Yellow	
		Green.
	Blue	

There are many interesting topics connected with the spectrum, the details of which I feel precluded from entering into, inasmuch as these lectures are intended to illustrate the phenomena of polarized light. I must, therefore, content myself with briefly naming some of them. The first is the *unequal refrangibility* of the difrent-coloured rays; the red being the least, the violet the most refrangible. It is in virtue of this property that lenses and prisms produce the phenomena of *dispersion* or *chromatic aberration.* Newton thought that the size of the spectrum, or the dispersive power of the refractive medium, was proportional to its refractive power; and, therefore, that the refracting telescope could not be made *achromatic.* In this he was mistaken. Equal refractions do not produce equal dispersions. Two lenses made of different kinds of glass, as one of crown the other of flint glass, may be so ground that the dispersions shall neutralize each other, while their refractions, not being equal, cannot neutralize; consequently, an excess of one remains.

Not the least remarkable fact connected with the spectrum, is the existence of *bands* or *fixed lines* in it. They are commonly called *Fraunhofer's lines of the spectrum.* The best mode of seeing them is to examine the spectrum by a telescope*. The light (as of a lamp, or that produced by throwing the oxyhydrogen flame on lime) should be passed through a bottle filled with nitrous acid vapour before it falls on the prism, to produce the spectrum.

The illuminating, heating, magnetic, and chemical powers of the spectrum, I must pass over without further notice, as they have no direct connection with the immediate object of this course of lectures. I cannot resist, however, remarking that the existence of a calorific, magnetic, and chemical influence beyond the confines of the coloured spectrum, is a fact of considerable importance in any enquiries which may be instituted into the nature of light. Moreover, the splendid and interesting pictures called *Daguerreotypes*, *Calotypes**, *Chrysotypes*, and *Ferrotypes, or Cyanotypes*, now before me, produced by the chemical influence of light on gross or ponderable matter, show the high importance of investigations respecting the chemical powers of the spectrum.

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* An apparatus for the exhibition of these lines, lent by Messrs. Watkins and Hill, was exhibited to the meeting.

7. *Diffraction.*—When light passes near the edges of bodies, it suffers certain modifications, included by opticians under the denomination of *inflection* or *diffraction*. If an opake body be placed in a cone of light admitted into a dark chamber through a very small aperture, its shadow is larger than its geometric projection. Moreover, its shadow is bordered with fringes, and similar fringes are observed within the shadows of narrow bodies.

If the light be homogeneous or monochromatic, the fringes consist of dark and light spaces of the same colour, and are of different breadths, red yielding the broadest, violet the narrowest fringes, but in white light the fringes are prismatic or iris-coloured.

The iris fringes may be readily observed by looking through the slit, between the almost closed fingers, at a candle, placed at a distance of several yards. It may be seen still better by looking at the same luminous body through a feather, or through a fine wire gauze. I have before me Schwerd's very complete apparatus for examining the complicated and difficult phenomena of diffraction.

When I tell you that the immortal Newton failed to perceive the internal fringes, and that he left the subject altogether in an imperfect, unsatisfactory, and unfinished state, I need scarcely add, that the phenomena are very complicated, and their study exceedingly difficult.

8. *Colours of thin plates, of films, and of grooved surfaces.* A variety of curious and brilliant optical phenomena were attributed by Newton to what he called *fits of transmission*, and *fits of reflection;* but which Dr. Young and most subsequent writers ascribe to *interference of light.* I refer now to the *phenomena of thin plates, of films, and of grooved surfaces.*

Excessively thin plates of air, liquids, or solids, appear coloured when viewed by reflected and transmitted light; but the colour seen by reflection is complementary to that seen by transmission.

If the plate be of uniform thickness, the colour is uniform; but if the thickness varies, the colour also varies.

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* Some beautiful Calotype portraits, taken by Mr. Collen, of Somerset Street, Portman Square, miniature painter to the Queen, were exhibited to the meeting.

Very much thinner plates than those which present colours, do not reflect light, and when viewed in this position, appear black. But they still transmit light, and when viewed by transmitted light, appear white.

Wedge-shaped plates present a series of parallel bands or fringes of colour.

A plate having the form of a plano-concave lens, the thinnest part of the plate being in the centre, gives a series of concentric rings of brilliant colours. Those seen by reflected light, have a black spot in the centre, while the transmitted rings have a white spot in the centre.

These different phenomena of thin plates are brilliantly illustrated in the lecture-room by the oxyhydrogen lime-light, which, after passing through the condensers of the lantern, is polarized, then passed through films of selenite (of uniform thinness, or wedge-shaped plates, or plano-concave films) afterwards through the two lenses called the powers, and ultimately analysed by a plate of tourmaline, or a bundle of plates of thin glass. The nature of the changes will be explained hereafter.

The squares of the diameters of the reflected coloured rings are as the odd numbers, 1, 3, 5, 7, 9, &c.; while the squares of the diameters of the transmitted rings are as the even numbers, 0, 2, 4, 6, 8, 10, &c.

The brilliant colours, produced by thin plates of air between the laminæ of mica, of selenite, and of Iceland spar, and between plates of glass, are familiar illustrations of the colours caused by thin plates of a gaseous substance.

The colours caused by thin films of oil of turpentine or other essential oils, of alcohol or of water, and by soap-bubbles, are well-known examples of the colours caused by thin plates of liquids.

The iridescent hues produced on copper or steel by heat, and which depend on the formation of a thin film of metallic oxide, are good illustrations of the colours caused by thin plates of solids. But the most brilliant are those caused by thin films of peroxide of lead, formed upon polished steel plates, by the electrolytic decomposition of acetate of lead. These splendid prismatic tints were discovered by Nobili*, and are commonly known as *Nobili's colours* or *metallo-chromes*. The mode of producing them has been described by my friend Mr. Gassiot, in a paper read before the Royal Society†. If we place on the polished steel plate a card screen in which some device is cut out, very beautiful figures, having a splendid iridescent appearance, are produced.

In all the cases hitherto alluded to, I have supposed white or

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[*] See Taylor's *Scientific Memoirs*, vol. i. part 1.

[†] See the *Proceedings of the Royal Society*, for March, 1840; also Brande's *Manual of Chemistry*, 5th edit., p. 836.

compound light to be used; and then the colours are iridescent or prismatic. But if monochromatic or homogeneous light be employed, the rings are of a uniform tint cr colour, and are separated by obscure bands or rings. Red light yields the broadest, violet light the narrowest rings.

Minute particles, fibres, and grooved surfaces also produce prismatic or iridescent colours by white light. Thus, minute particles of condensed vapour, obtained by breathing on glass, give rise to this effect. A familiar illustration is to be found in the halos observed around the street-lamps, when viewed at night through a coach-window, on the glass of which vapour is deposited. In this case the colours are seen by transmission. Dr. Joseph Reade's beautiful instrument, called the *Iriscope*, brilliantly displays the colours produced by reflection from a plate covered with condensed vapour. It consists of a plate of highly-polished black glass, having its surface smeared with a solution of fine soap, and subsequently dried by rubbing it clean with a piece of chamois leather. If the surface, thus prepared, be breathed on, through a glass tube, the vapour is deposited in brilliant coloured rings. But as, in this mode of experimenting, the plate of vapour is thickest in the middle, and thinnest in the circumference, the rings have black circumferences instead of black centres.

Minute fibres of silk, wool, and of the spider's web, also present in sunshine a most vivid iridescence.

A very minutely grooved surface also presents a prismatic or iridescent appearance in white light. Of this mother-of-pearl is a familiar instance—as also opal. Micrometer scales frequently present the same appearances; and Barton's buttons and other iris ornaments owe their resplendence to the numerous minute grooves cut in the surface of the metal. If a beam of light from the oxyhydrogen apparatus be received on one of Barton's buttons, an iridescent image may be thrown on a screen several yards distant; thus furnishing a good lecture-room illustration of the colours of grooved surfaces.

9. *Double Refraction.*—When a pencil of light falls in certain directions on any crystals, which do not belong to the cubical system, it is split or divided into two other pencils, which diverge and follow different paths; and when their divergence is considerable, objects viewed through them appear doubled. The change thus effected on a ray of light is denominated *double refraction*. The substance which is commonly used to produce this effect is that variety of transparent crystallized carbonate of lime, called *Iceland spar*, or sometimes *calcareous spar*, or, for brevity, *calc-spar*.

In every double refracting crystal there are, however, one or more directions in which double refraction does not take place. These are called *axes of double refraction:* they might with more propriety be termed *axes of* NO *double refraction*.

I now pass a beam of light (produced by throwing the oxy-hydrogen flame on lime) through a rhombohedron of Iceland spar, and we obtain two images on the screen. By rotating the crystal on its axis, one of the images revolves around the other, but neither disappears during the revolution. Now this fact proves that the light which falls on the crystal is unpolarized; for if it had been polarized, one image would have disappeared in certain positions, as I shall hereafter prove.

10. *Polarization.*—When submitted to certain influences, the rays of common light acquire peculiar properties, designated by the term *polarization.* These peculiarities are not distinguishable by the unassisted eye.

A very common question, put by persons who have not studied the subject, is, "*What is polarized light?*" and the philosopher feels very considerable difficulty in giving a concise and intelligible reply; so that the enquirer, perhaps after listening to a lengthened detail, frequently goes away, without obtaining as he says, a direct and short answer to his question.

There are two modes of reply: *one* is to describe, independent of all hypotheses, the properties by which polarized light is distinguished from common light; the *other,* is to adopt some hypothesis of the nature of light, and, therefore, to give an hypothetical explanation of the nature of polarized light. Whichever method we adopt—and I shall give both—lengthened details are necessary to enable the uninitiated to comprehend the subject.

There are four methods of polarizing light, *viz.*

a. Reflection.
b. Simple refraction.
c. Double refraction.
d. Transmission through a plate of tourmaline.

In the following table I have contrasted some of the distinguishing characteristics of common and polarized light:

A Ray of Common Light,	*A Ray of Polarized Light,*
1. Is capable of *reflection,* at oblique angles of incidence, in every position of the reflector.	1. Is capable of *reflection,* at oblique angles of incidence, *in certain positions only* of the reflector.
2. Penetrates a plate of *tourmaline* (cut parallel to the axis of the crystal) in every position of the plate.	2. Penetrates a plate of *tourmaline* (cut parallel to the axis of the crystal) in certain positions of the plate, but in others is wholly intercepted.
3. Penetrates a *bundle of parallel glass plates,* in every position of the bundle.	3. Penetrates a *bundle of parallel glass plates,* in certain positions of the bundle, but not in others.
4. Suffers *double refraction* by Iceland spar in every direction, except that of the axis of the crystal.	4. Does not suffer *double refraction* by Iceland spar in every direction, except that of the axis of the crystal. In certain positions, it suffers single refraction only.

Thus, then, one mode of replying to the before-mentioned question would be, by recapitulating the facts stated in this second column. This reply would form what I may term a matter-of-fact answer, being independent of all hypothesis.

The naked or unassisted eye cannot then distinguish common from polarized light. Every person must have repeatedly seen polarized light, but not knowing how to recognize it, has failed to distinguish it from common light. If you look at a polished mahogany table, placed between you and the window, part of the light reflected from the table is polarized. When you look obliquely at the goods in a linendraper's shop, through the plate-glass window, part of the light by which you see the articles is polarized. When you see two images by a crystal of Iceland spar the transmitted light is polarized. The atmospheric light is frequently polarized, especially in the earlier and later periods of the day when the solar rays fall very obliquely on the atmosphere. At the present season, the effect may be perceived at eight or nine o'clock in the morning and five or six o'clock in the afternoon, the observer standing with his back to the sun, or with his face north or south. I have found that the effect is best perceived when the sun is shining, and the atmosphere more or less misty.

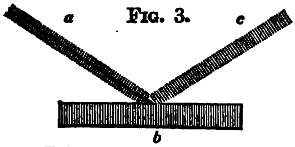
It is obvious, therefore, that after we have polarized a ray of light, we must employ some agent to detect its peculiar properties. This agent is called the *analyser*. It would be better understood if it were termed the *test*. It may be a *reflecting plate*, *a plate of tourmaline*, *a bundle of glass plates*, *a Nichol's prism*, or *a double refracting prism*; in fact, the analyser or test must be a polarizer.

Thus, then, a *polariscope* consists of two parts: one for polarizing, the other for analysing or testing the light. There is no essential difference between the two parts, except what convenience or economy may lead us to adopt; and either part, therefore, may be used as polarizer or analyser; but whichever we use as the polarizer, the other then becomes the analyser.

a. Polarization by reflection.—This method of polarizing light was discovered by Malus, in 1808. He was viewing, through a double refracting prism, the light of the setting sun reflected from the glass windows of the Luxemburgh palace in Paris; and, on turning round the prism, he was surprised to observe a remarkable difference in the intensity of the two images: the most refracted alternately surpassing and falling short of the least refracted in brightness.

Polarizing reflectors are usually *glass*. This should be either ground or blackened at the back to prevent posterior reflection. *Water* is seldom made use of. *Mica* may be employed instead

FIG. 3.



Polarisation by Reflection.
a. Incident ray of common or unpolarized light.
b. Plate of glass (*polarizing plate*).
c. Reflected ray of polarized light.

of glass. *A well-polished* or *varnished piece of wood* (as a table, top of a pianoforte, or a counter) is very convenient. *Marble* also answers tolerably well. The *shining back of a book* is oftentimes serviceable. Metallic plates are objectionable; since by one reflection only from them, the light is found to be elliptically polarized; though by successive reflections it becomes plane polarized.

The polarizing angle varies for different substances, as the following table shows:

Angles of Polarization by reflection.

Water . . .	52° 45′
Glass	56° 45′
Sulphate of lime	56° 45′
Rock crystal .	56° 58′
Iceland spar . .	58° 51′
Diamond . . .	68° 1′

From a very extensive series of experiments, made to determine the maximum polarizing angles of various bodies, Dr. Brewster arrived at the following law: *the index of refraction is the tangent of the angle of polarization.* It follows, therefore, that *the reflected polarized ray forms a right angle with the refracted ray.*

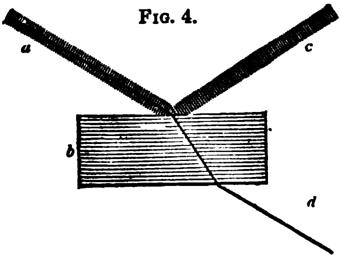
Here, perhaps, is the most convenient place for referring to a suggested application of polarized light. I have stated that light is polarized by water, at an angle of 52° 45′. By the analyser (as a tourmaline, or Nichol's prism, or a bundle of glass plates) the whole of this reflected polarized light may be intercepted without offering any impediment to the unpolarized but refracted light which has traversed the water; so that objects may be more readily seen at the bottom of ponds, rivers, and the sea, by this expedient than otherwise, since the glare of the reflected light is prevented. Hence anglers, and those fond of fish-spearing, may employ this property of polarized light in the discovery of the objects of their sport; and commanders of vessels may avail themselves of it to detect rocks and shoals in the bottom of the ocean, which are not otherwise visible except by viewing them from the mast-head, by which the angle of reflexion is diminished, and consequently the quantity of light reflected is thereby lessened.

I proceed now to demonstrate the polarization of light by reflection, and the essential properties of the polarized ray. For this purpose, I obtain an intense light by throwing the flame of a jet of mixed oxygen and hydrogen gases on a cylinder of lime.

This light, which I shall, for brevity, call the *lime-light*, is condensed by two crossed lenses (called *condensers*), and thrown on a plate of glass, blackened at the back, and placed at an angle of 56° 45′. The light is polarized by this plate, and being then refracted by two plano-convex glasses (termed the *power*), is afterwards received on a semi-transparent calico screen, strained on a wooden frame, and moistened with water. A bundle of glass plates is sometimes used as a reflecting polarizer: it has the advantage of reflecting more light, but a portion of it is unpolarized.

The light thus polarized is not distinguishable by the eye from common light, but to prove its nature, I proceed to test it. For this purpose, I place a plate of tourmaline on the front of the polariscope, and on revolving it, you observe the light on the screen is alternately cut off and admitted. At 0 the tourmaline transmits the light, at 90° it absorbs it, at 180° it transmits it, at 270° it absorbs it. I remove the tourmaline, and substitute a bundle of glass plates, placed at an angle of 56° 45′. On revolving this, the light is observed to be alternately cut off and transmitted, as in the case of the tourmaline. I now substitute a double refracting prism for the bundle of glass, and on revolving this, it is seen that in two positions double refraction takes place, and two images are produced on the screen, while in two intermediate positions, one image is cut off. Thus, then, the light reflected from the blackened glass plate of the polariscope, is polarized, since it possesses the characters assigned to this kind of light.

FIG. 4.



Polarization by single Refraction.
a. Ray of common or unpolarized light.
b. Bundle of glass plates.
c. Reflected polarized ray.
d. Refracted polarized ray. This ray is oppositely polarized to *c.*

2. *Polarization by single Refraction.*—If light be transmitted obliquely through a bundle of diaphanous laminæ, it suffers polarization. The very thin parallel glass plates used for microscopes, and sold by Bromley and Drake, at 315, Oxford Street, form the best medium. Sixteen or more of these are to be placed parallel, and the bundle then placed at an angle of 56° 45′ to the ray to be polarized.

Common crown or window glass serves well enough for ordinary purposes. The flattest, thinnest, most colourless, and perfect pieces are to be selected. A very convenient mode of using them is the following:—Take two one ounce paper pill-boxes, remove the lids and the bottoms, and then paste together the two cylinders of the boxes, so as to form a tube. Into this, place obliquely sixteen pieces of window glass.

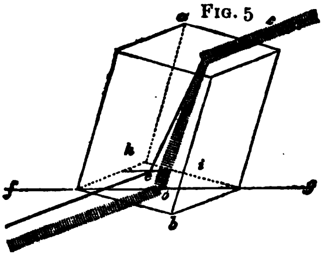
Having cut in each of the lids a circular hole, of about the size of a sixpence, place a lid at each end of the cylinder. The light by passing obliquely through the glass-plates in this cylinder, becomes polarized.

A bundle of mica plates may be used for polarizing, but it is inferior to the bundle of microscope glass above referred to.

3. *Polarization by Double Refraction.*—I have already demonstrated the double refractive power of Iceland spar; though I have not hitherto said anything of the nature of the light of which the two pencils are made up.

I now proceed to demonstrate that the two pencils or rays produced by this process are polarized; but the polarized state of the one ray is of an opposite kind to that of the other; so that the two rays are said to be *oppositely polarized*. That this is the case is proved by applying our tests to them. Thus, if I apply a plate of tourmaline, you observe that, as this is rotated, one of the luminous rays is alternately cut off, which would not be the case were the rays composed of common light; while, if both were similarly polarized they would be simultaneously and not alternately absorbed. If I substitute the bundle of glass plates for the tourmaline, one of the rays is reflected, and the other transmitted; and by revolving the bundle 90°, the ray which was reflected is now transmitted, and that which was transmitted is now reflected.

FIG. 5



Double Refraction by a rhombohedron of Iceland Spar.

a. b. The obtuse angles. A line drawn from *a* to *b* represents the axis of the crystal.

c. Incident ray of unpolarized or common light.

e. o. Oppositely polarized transmitted rays, *e* is called the extraordinary, *o* the ordinary ray.

f. g. A line, which when viewed through the rhombohedron, appears doubled, *f g* and *h i*.

Nichol's prism, or *Nichol's eye-piece**, is a most valuable and convenient polarizer. It is an oblique rhombic prism, whose terminal planes form an angle of 68° with the adjoining obtuse lateral edges. It is formed by joining, by means of Canada balsam, two wedge-shaped pieces of Iceland spar. It is a double refractor, but the two rays are made to deviate so far, that only one image is seen in its usual position. The cause of this is the Canada balsam, whose index of refraction (1.549) is intermediate between that for the ordinary ray (1.654), and that for the extraordinary ray (1.483), so that this substance changes the direction of the two rays in an opposite manner, before they enter the posterior half of the prism. Over the tourmaline this prism has the advantage of being perfectly free from colour, but it has the great objection of giving a very limited field of vision.

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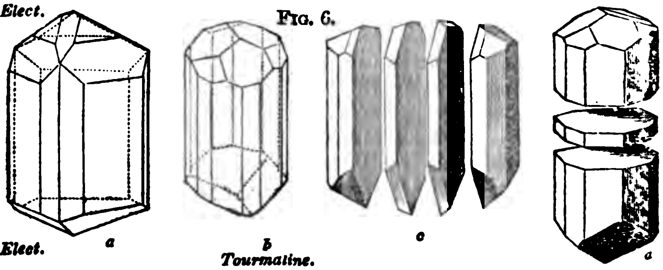
* See *Jameson's Journal*, vols. 6, 16, and 27.

4. ***Polarization by the Tourmaline.*** The last mode of polarizing light to which I shall have occasion to allude, is by transmission through a plate of tourmaline, cut parallel to the axis of the crystal.

The substance called *tourmaline*, and to which I have already referred, is a precious stone, which is occasionally cut and polished, and worn as a jewel. There is good reason for supposing that it is the substance to which Theophrastus alludes under the name of *lyncurium* (λυγκύριον). It is found in various parts of Europe, Asia, Africa, and America. Much of that found in commerce comes from the Brazils. It occurs in thick and short, as well as in acicular prismatic crystals, belonging to the rhombohedric system, and which have three, six, or more sides and dissimilar summits. Thus in most tourmalines the extremities or summits of the crystal differ from each other in the number or situation of the planes; and like other unsymmetrical crystals, the tourmaline becomes electrical while changing its temperature, one extremity becoming positive, the other negative.

Fig. 6.



a. Brazilian tourmaline. By cooling, the upper end becomes positively (+), the lower negatively (—) electrical.
b. Another tourmaline.
c. Tourmaline slit, parallel to the axis, into four plates, which, when ground and polished, are used as either polarizers or analysers.
d. Tourmaline cut at right angles to its axis. The plates, thus obtained, are ground and polished, and then used in the polariscope for producing coloured rings.

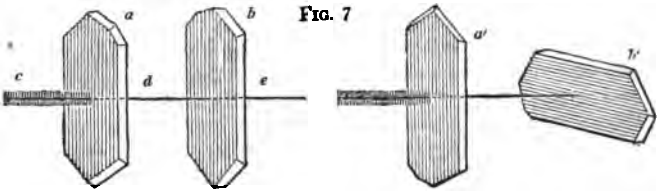
The colour of the tourmaline is various, but green and brown are the prevailing tints. Curiously enough, there appears to be a remarkable connection between the colour and the other optical, as well as the electrical properties of the tourmaline. Green, blue, and yellow colours are, in general, imperfect polarizers. The brown and pinkish tints are the best. White colourless tourmalines do not polarize.

The principal constituents of the tourmaline, are *silica* and *alumina. Boracic acid* is always present, as also *magnesia. Iron, potash, soda, &c.*, are not constant ingredients.

For optical purposes, the tourmaline is cut in two directions, viz. *parallel*, and likewise at *right angles to the crystallographical axis.* Tourmaline plates for *polarizing or analyzing*, are cut parallel to the axis about $\frac{1}{20}$ of an inch thick; but for depolarizing, or showing coloured rings, at *right angles to the axis.* Considerable care and experience are required to prepare good plates.* If they be not cut perfectly parallel to the axis, their polarizing and analyzing powers are greatly impaired. In buying plates, avoid cracks, flaws, and deep colours, and select those which by experiment you find to be good polarizers, for as the polarizing powers are very unequal in different crystals, nothing but a trial of each plate can determine its goodness.

The light which is transmitted by a plate of tourmaline (*a* or *a*′) (cut parallel to the axis), is plane-polarized. A second plate of tourmaline (*b*), if held in the same position, transmits the light polarized by the first plate; but if the second plate (*b*′) be turned round, so that its axis is at right angles with the axis of the first plate, no light is transmitted.

FIG. 7



Action of Tourmaline Plates on Light.

a. b. **Two plates of tourmaline (cut parallel to the axis of the crystal), with their axes coincident; *a.* is called the polarizer, and *b.* the analyser.**

c. **Incident ray of unpolarized light.**

d. **Transmitted ray of light polarized by *a*.**

e. **Ray polarized by *a*, and transmitted by *b*.**

a′. b′. **Two plates of tourmaline with their axes opposed, so that the light, polarized by *a′*, is intercepted by *b′*.**

The great objection to the tourmaline, as a polarizer, is, that the transmitted polarized beam is more or less coloured. If large, transparent, and colourless polarizing tourmalines could be obtained, they would be invaluable to the optician.

That common light is polarized by transmission through a plate of tourmaline, as above described, is proved thus: — A second tourmaline, placed with its axis at right angles to the first, does not permit light to pass. But when the axes of the plates coincide, the light polarized by the first plate is trans-

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*** Mr. Darker, of Paradise Street, Lambeth, prepares tourmaline plates for most of the opticians.**

mitted by the second. Moreover, if the light transmitted through the first tourmaline be received at an oblique angle on a plate of glass, blackened at the back, it is reflected only on two sides of the ray, and at an angle of 56° 45′. Lastly, if it be tested by a double refracting prism, it is found to produce double refraction in two positions only of the ray, for on rotating the double refracting prism on its axis, we find that one of the images is alternately cut off, and in intermediate positions, two faint images only are produced.

2. WAVE HYPOTHESIS OF LIGHT.

There are two hypotheses or theories which have been formed to account for the phenomena of light; one of these is called, the *projectile theory*, or the *theory of emission*;—while the second is denominated the *wave*, or *undulatory theory of light*.

The first is sometimes called the *material* or *Newtonian theory* of light. But as on both hypotheses a fine subtile form of matter is required to account for luminous phenomena, the one hypothesis equally deserves the name of *material* with the other. Moreover, I cannot understand why the projectile theory is to be exclusively honoured with the name of the *Newtonian*; for though on some occasions Newton certainly adopts it, yet on others he appears to support the theory of waves.

On the present occasion it is not my intention to enter into any details respecting the projectile theory; for however ably and plausibly it accounts for some optical phenomena, it is manifestly incompetent to explain those which it is the object of this course of lectures to describe.

Light, a Property or Motion.—The wave-theory supposes that light is a *property*—a *motion*—a *vibration* of something. But of what? Euler imagined that the vibrating medium, in dense bodies, was the body itself; through the gross particles of which he supposed the light to be propagated in the same manner as sound. This hypothesis, Dr. Young* declares to be "liable to strong objections;" and he adds, that "on this supposition, the refraction of the rays of light, on entering the atmosphere from the pure ether which he describes, ought to be a million times greater than it is."

Ether.—To account for the phenomena of light, philosophers have assumed the existence of a vibrating medium, which has been called *the ethereal medium*, the *luminiferous ether*, or simply

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* *A Course of Lectures on Natural Philosophy*, vol. ii., p. 542. Also *Phil. Trans.* for 1800.

ether. It is supposed to be a rare, highly elastic, subtile fluid, which occupies all space and pervades all bodies. As the sensation of light is supposed to be excited by the undulations of this medium, so, where light exists, there ether must be. Hence it fills all space. It is between the sun and the earth, the earth and the stars, and so on. If it did not exist in water, diamonds, glass, &c., these bodies would not be diaphanous. So that it must pervade all bodies. Even opake substances must contain it, since, as in the case of gold, these become transparent when excessively thin.

Existence of an Ether.—We have no independent evidence to adduce of the existence of this medium. It is, therefore, an assumption; but one which is sanctioned by the high authority of Descartes, Huyghens, Euler, Hooke, Newton, Young, Fresnel, and some of the most distinguished philosophers of the present day, among whom are Sir John Herschel and Arago. These eminent men have seen in this assumption nothing inconsistent with their knowledge of the constitution of the universe. The electrician and the magnetician have assumed, respectively, an electric and a magnetic fluid, and there can be no impropriety, therefore, in the optician assuming a luminiferous ether, provided, however, that it be compatible with well ascertained facts, and do not violate known laws. Moreover, it is by no means improbable that the fluids which have been respectively assumed as the causes of electrical, magnetical, calorific, and luminous phenomena, may be one and the same.

Even gravity, perhaps, may be referable to the same cause. Newton* himself has thrown out a speculation of this kind. Alluding to the ether, he says, "Is not this medium much rarer within the dense bodies of the sun, stars, planets, and comets, than in the empty celestial spaces between them? And in passing from them to great distances, doth it not grow denser and denser perpetually, and thereby cause the gravity of those great bodies towards one another, and of their parts towards the bodies; every body endeavouring to go from the denser parts of the medium towards the rarer?" Very recently, Dr. Roget † and Mosotti ‡ have shown how, on the assumption of an ethereal medium, the phenomena of gravitation and electricity, may be included in the same law.

It has been said, that if the universe contained a fluid of the kind here referred to, the planets must experience some resistance to their motions, and, therefore, that as no resistance can be detected, there can be no ethereal medium. This conclusion, however, is by no means a necessary one, for "if this ether," says Newton*, "should be supposed 700,000 times more elastic than our air, and above 700,000 times more rare, its resistance would be above 600,000,000 times less than that of water. And so small a resistance would scarce make any sensible alteration in the motions of the planets in ten thousand years." The most satisfactory evidence of this resistance, if indeed it exist, might be expected to be found in the case of the comets, bodies made up of the lightest materials, in fact, masses of vapour, and, therefore, from their less momentum, more likely to suffer retardation. In the case of Encke's comet, evidence of this resistance is believed to have been obtained. The mean duration of one entire revolution of this comet is about 1207 days, and the "magnitude of the resistance is such as to diminish the periodic time about $\frac{1}{10000}$ of the whole at each revolution; a quantity so large that there can be no mistake about its existence.†"

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* *Opticks*, p. 325. Query 21.

† *Electricity*. Published in the *Library of Useful Knowledge*.

‡ *On the Forces which regulate the Internal Constitution of Bodies*, in Taylor's *Scientific Memoirs*, part iii.

The following table of the mean duration of one entire revolution of this comet, allowance being made for perturbations occasioned by the action of neighbouring planets, is taken from a memoir by Encke‡.

	Days.
From 1786 to 1795…………	1208.112
" 1795 to 1805…………	1207.879
" 1805 to 1819…………	1207.424

Sir John Herschel § observes, that "on comparing the intervals between the successive perihelion passages of this comet, after allowing, in the most careful and exact manner, for all the disturbances due to the actions of the planets, a very singular fact has come to light, viz., that the periods are continually diminishing, or, in other words, the mean distance from the sun, or the major axis of the ellipse, dwindling by slow but regular degrees. This is evidently the effect which would be produced by a resistance experienced by the comet from a very rare ethereal medium pervading the regions in which it moves, for such resistance, by diminishing its actual velocity, would diminish also its centrifugal force, and thus give the sun more power over it to draw it nearer. Accordingly (no other mode of accounting for the phenomenon in question appearing) this is the solution proposed by Encke, and generally received. It will, therefore, probably fall ultimately into the sun, should it not first be dissipated altogether, a thing no way improbable, when the lightness of its materials is considered, and which seems authorized by the observed fact of its having been less and less conspicuous at each reappearance."

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* *Opticks*, p. 327. Query 22.

† Airy, *Report on the Progress of Astronomy, in the Report of the British Association for* 1833.

‡ *Astronomische Nachrichten*, Nos. 210, 211.

§ *Treatise on Astronomy* (in *Lardner's Cyclopædia*), p. 309.

Leaving these speculations, and assuming, then, the existence of a luminiferous ether, I proceed to point out the properties such a fluid must be supposed to possess.

Ethereal Molecules.—The ether consists, or is made up of minute parts, which we call *molecules,* between which there must exist attractive and repulsive forces *, in virtue of which the ether possesses extreme elasticity. Moreover, there appears to exist some attractive force between the ethereal molecules and the particles of the grosser forms of matter. Indeed, Dr. Young supposed that the vibrating medium is the ether and ponderable matter conjointly.

But instead of insisting on the actual existence of an ethereal medium composed of molecules, we "may be content to look at the theory simply as a mathematical system, which faithfully represents, at least, a wide range of phenomena, and to some extent connects the laws so made out with dynamical principles regulating the motions of a system of points, combined to form an elastic system, which, for *brevity* and *illustration, we call molecules,* constituting an *æthereal medium* †."

Ethereal Waves.—If we suppose the existence of attractive and repulsive forces between the ethereal molecules, it follows, that when these molecules are at rest or have attained a state of equilibrium, any attempt to move one molecule must be attended with the displacement of several; for the motion is extended to adjacent molecules. So that if a vibratory movement be communicated to one, it is extended to several. Now, an assemblage of vibrating molecules, in all phases of vibration, constitutes an *ethereal wave.* These vibrations being communicated through successive portions of the ethereal medium, reach the retina or expanded optic nerve, and are propagated along the optic nerve to the brain, where they excite in us the *sensation of light,* just as the vibrations of the air communicated to the auditory nerve, and from thence to the brain, produce the sensation of sound.

The number of impulses made by the ethereal molecules on the retina in a given time, determines the *colour of the light,* just as the number of impulses by the aerial molecules on the auditory nerves determines the *pitch, note,* or *tone* of sound. Hence colours are to the eye what tones are to the ear.

"From Newton's measures of the thicknesses reflecting the different colours, the breadth and duration of their respective undulations may be very accurately determined. The whole visible spectrum appears to be comprised within the ratio of three to five, which is that of a major sixth in music; and the undulations of red, yellow, and blue, to be related in magnitude as the numbers 8, 7, and 6; so that the interval from red to blue is a fourth. The absolute frequency expressed in numbers is too great to be distinctly conceived, but it may be better imagined by a comparison with sound. If a chord sounding the tenor $\bar{c}$, could be continually bisected forty times, and should then vibrate, it would afford a yellow green light: this being denoted by $\overset{41}{C}$, the extreme red would be $\overset{40}{A}$, and the blue $\overset{41}{D}$. The absolute length and frequency of each vibration is expressed in the table*;" supposing light to travel at the rate of 192,000 miles per second.

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* See a paper by Mr. Earnshaw, *On the Nature of the Molecular Forces which regulate the Constitution of the Luminiferous Ether,* in the *Transactions of the Cambridge Philosophical Society,* vol. vii., part 1.

† *A General and Elementary View of the Undulatory Theory, as applied to the Dispersion of Light.* By the Rev. Baden Powell, 1841, pp. 4 and 5.

COLOURS.	Length of an Undulation in parts of an inch in Air.	Number of Undulations in an inch.	Number of Undulations in a second.
Extreme.........	.0000266	37640	458 millions of millions.
Red.....................	.0000256	39180	477 "
Intermediate ...	.0000246	40720	495 "
Orange	.0000240	41610	506 "
Intermediate ...	.0000235	42510	517 "
Yellow	.0000227	44000	535 "
Intermediate ...	.0000219	45600	555 "
Green	.0000211	47460	577 "
Intermediate ...	.0000203	49320	600 "
Blue	.0000196	51110	622 "
Intermediate ...	.0000189	52910	644 "
Indigo	.0000185	54070	658 "
Intermediate ...	.0000181	55240	672 "
Violet	.0000174	57490	699 "
Extreme.........	.0000167	59750	727 "
Mean of all, or white	.0000225	44440	541 "

There is a *limit to the sensibility of both ear* and *eye;* that is, a certain number of impulses must be made in a given time on these organs before we become sensible of them; and if we go on augmenting the number, we cease to be sensible of them after a certain time. Now, the limits of sensibility of the eye are much more confined than those of the ear; or, in other words, the sensibility ceases much sooner in the case of the eye than in that of the ear.

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* Dr. Young's *Course of Lectures on Natural Philosophy*, vol. ii. p. 627. The above table is also taken from this work. Dr. Young calculated the velocity of light at 500,000 million feet in 8¼ minutes; but I have adopted Sir John Herschel's assumption of 192,000 miles per second, which makes the numbers in the fourth column of the table different to those given by Young.

The following is the range of the human hearing according to Biot*:—

	Number of Vibrations in one second.	Length of Sonorous Waves.
		Feet in.
Commencement of appreciable Sounds......	32	32 0
	64	16 0
	128	8 0
	256	4 0
	512	2 0
	1024	1 0
	2048	0 6
	4096	0 3
End of appreciable Sounds....................	8192	0 1½

But the actual range varies in different individuals, and we shall not be far from the truth if we assume, with Dr. Wollaston† and Sir John Herschel‡, that the whole range of human hearing includes about nine octaves.

Now on comparing the range of human hearing with that of vision, we find the relative limits of the two senses to be as follows:—

	Eye.	*Ear.*
Commencement of sensibility .	1	1
Cessation of ditto	$1\frac{58}{100}$ . .	1024

It is highly probable, however, that the range of human vision, like that of hearing, is subject to variation in different individuals.

From these observations, then, it will be understood, that, according to the undulatory theory, the *colour* of the light depends on the lengths of the waves, or on their number in a given time. Thus *red* has the largest waves, and, therefore, the smallest number in a given time; while *violet* has the shortest waves, and, therefore, the greatest number in a given time.

The *intensity* of the light depends on the amplitude or extent of excursion of the ethereal molecules from their points of rest; or in other words, on the height of the wave. Just as when we make a cord sound, we find that the sound diminishes in proportion to the diminution of the amplitude of the oscillations.

Vibrations.—The *vibrations* of the ethereal molecules may be *rectilinear* or *curvilinear*. It is not easy to give a popular illustration of the first, which, however, may be easily conceived; but the motion of a pendulum is an excellent example of curvilinear motion. A ball, suspended by a string, describes in vibrating a curved line, or, in other words, it vibrates in the arc of a circle.

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* *Précis Elémentaire de Physique*, vol. i. p. 324.

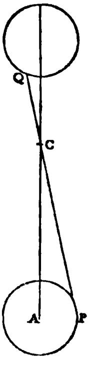
† *Phil. Trans.* 1820, p. 306.

‡ *Encyclopædia Metropolitana*, art. *Sound*, p. 792.

An assemblage of molecules, vibrating *rectilinearly*, in the same plane, and in all phases of their vibrations, constitutes a *plane wave*. An assemblage of molecules, vibrating *curvilinearly* or *rotating*, the rotation or vibration of every molecule being made in parallel planes, constitutes what may be termed a *spiral* or *helicoidal wave*. If the molecule revolve in a circle, the wave is *circular*; if in an ellipse, the wave is *elliptical*.

All motion being naturally rectilinear, it follows, that when we see a body moving in a curve of any kind, we conclude that it must be under the influence of at least two forces; one putting it in motion, and another drawing it off from the rectilinear course, which it would otherwise have continued to move in. The cause of these curvilinear movements of the ethereal molecules will be subsequently explained.

FIG. 8.



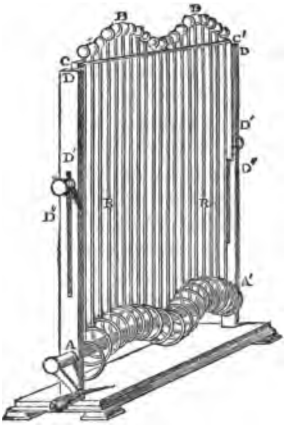
The Rev. Professor Baden Powell has contrived an ingenious machine, for showing in what manner rectilinear and curvilinear vibrations produce respectively plane and helicoidal (circular or elliptical) waves. It is founded upon this geometrical construction: a finite line, *P Q*, moves always through the point *C*, and with its end *P* always in the circumference of a given circle, whose centre is *A*; the end *Q* will describe a certain curve, which appears upon analysis to be one of a high order, but having *in general* some sort of oval form, which varies as the distance *A C* is altered. If *A C* be very great compared with the radius of the circle, *Q* will move up and down, *almost* in a straight line: if *A C* be somewhat less, its path will *resemble* an ellipse; if still less, it will be more rounded or *resemble* a circle.

Upon this the machine is constructed as follows (*A* and *C* correspond in both diagrams):

The lower part consists of a stout iron wire bent into a series of cranks, of which the two extremes are in the same position, *e. g.* downwards; the middle one vertical, and the intermediate ones at intermediate inclinations. Attached to each crank by a hinge or joint, is a long rod, *R R'*, &c., which passes through an aperture in a cross-bar, *C C'*, at the top. The top of this rod is made conspicuous by an ivory ball or a ball painted white, *B*, the rest of the apparatus being painted black. The bar *C C'* is attached to the supports *A C A' C'*, by screws, and can be removed (without changing the rods) from *D D* to the positions *D' D'*, or *D'' D''*. The proportions of the machine are not essential, but only that the length of the rods should be great compared with that of the cranks. When the bar is at *D D*, on turning the handle a plane polarized wave is produced by the balls; when at *D′ D′* an elliptical one; and when at *D″ D″* a circular one—that is, what, for illustration, and to the eye, may be considered so. If the distance *A D″* be eighteen inches, *A D′* should be about twenty-four, and *A D* about thirty-six inches; but these are not material as to exactness.

Mr. E. M. Clarke, philosophical instrument-maker, of the Strand, has constructed this instrument without cranks. The upright rods are attached inferiorly to metallic rings, through each of which runs an axis, *A A′*; and on this axis the rings are fixed in a spiral or helicoidal manner.

FIG. 9.



Professor Powell's Machine, as constructed by Mr. Clarke.

Transversal Vibrations.—I come now to a most important part of the undulatory hypothesis—that by which the phenomena of polarized, as distinguished from those of common or unpolarized, light are accounted for. I refer now *to the hypothesis of transversal vibrations*, first suggested, I believe, by Dr. Young, but most admirably developed and applied by Fresnel.

"The existence of an *alternating motion of some kind*, at minute intervals along a ray, is," says Professor Powell,* "as real as the motion of translation by which light is propagated through space. Both must essentially be combined in any correct conception we form of light. That this alternating motion must have reference to certain directions *transverse* to that of the ray is equally established as a consequence of phenomena—and these two principles must form the basis of any explanation which can be attempted."

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* *A General and Elementary View of the Undulatory Theory*, p. 4.

In order to understand transversal vibrations, let us first consider how waves of water, and of other liquids, are formed. If a stone be thrown into a pond, there is formed a system or group of waves, which commences at the spot where the stone impinges, and gradually extends outwards in the form of concentric circles. The aqueous particles in the centre are forced down, and the surrounding ones thereby urged upwards above the normal level of the water. In this way the central depression, and the first or innermost circular heap, are formed. But gravity soon causes this heap to subside, and fill up the central depression, while by its downward progress it acquires momentum, and thereby descends below its normal level, thus not only giving rise to a circular depression, but causing the formation of another and outer circular heap by the elevation of the neighbouring particles. In this way the waves gradually extend outwards. It is obvious, then, that in *waves of liquids*, the directions of vibration of the molecules is *vertical*, or nearly so, while the propagation of the waves is *horizontal.*

In a vibrating cord, *the vibrations are rectangular to the propagation of the undulations* along the cord.

In *luminous waves*, the direction of vibration is supposed by Fresnel to be *transverse* to the direction of propagation; and the more recent researches of Cauchy seem to have established the doctrine of transversal vibrations; but he assumes a third vibration, namely, one *parallel* to the ray, so that, according to him, the motions of the molecules take place in *three rectangular axes.* The necessity for this third axis of vibration, parallel to the ray, seems to be derived from the phenomena of dispersion.

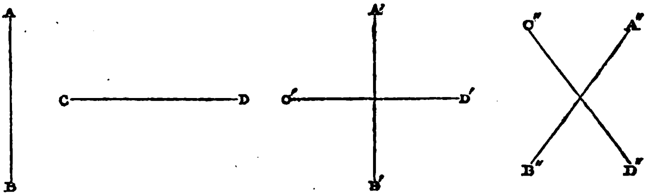
Now, *polarized light*, on the wave hypothesis, is light which has only one plane of vibration; whereas *common* or *unpolarized light* consists of light having two or more planes of vibrations, of which two must be rectangular—that is, after the molecules have vibrated in one plane, they change their vibration to another plane. So that common light consists in a rapid succession of waves in which the vibrations take place in different planes. It does not, however, appear that the planes of vibration are *continually* changing; but that in each system of waves, there are probably several hundred successive vibrations, which are all performed in the same plane; although the vibrations of one system bear no relation to those of another. Thus, then, we call that light *polarized*, in which all the vibrations take place in *one* plane; but when vibrations are succeeded rapidly by other vibrations in an opposite plane, the two waves though *separately* called *polarized*, are *together*, termed *unpolarized* or *common* light; so that, as Fresnel has observed, *common* light is merely *polarized light, having two planes of polarization at right angles to each other.*

Thus, then, I have now replied theoretically, as well as practically, to the question, "*What is polarized light?*"

Partially polarized light consists, according to Sir John Herschel, of two unequally intense portions; one completely polarized, the other not at all. Sir David Brewster, however, regards it as light whose planes of polarization are inclined at angles less than 90°. But to the latter view some objections have been raised by Mr. Lloyd.

In the following diagram, let the straight lines represent the directions in which the ethereal molecules are supposed to vibrate. Then *A B* and *C D* will represent the direction of vibration ot the ethereal molecules of two oppositely polarized rays; *A B′ C′ D′* the two rectangular directions of vibration of a ray of common or unpolarized light; and *A″ B″ C‴ D″* a ray of partially polarized light, according to Sir D. Brewster's hypothesis.

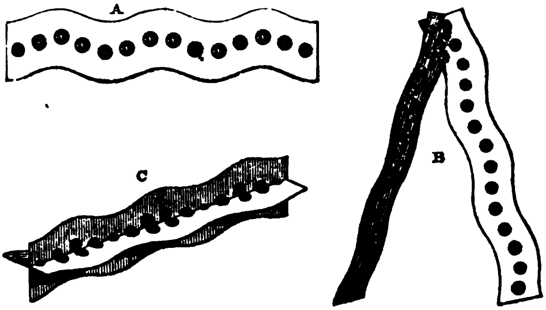
Fig. 10.



"The difference between a polarized and an ordinary ray of light," says Sir John Herschel, "can hardly be more readily conceived than by assimilating the latter to a cylindrical, and the former to a four-sided prismatic rod, such as a lath or a ruler, or other long, flat, straight stick."

In order to illustrate Fresnel's notion of transversal vibrations, and of the hypothetical difference between common and polarized light, *painted card models* are very convenient. A piece of card-board is cut out in a waved or undulated form, so that the curves of the upper and lower edges accord. Then, midway between these edges, a row of circular black spots is painted on the card: these are to represent the ethereal molecules, while the card-board represents the plane of vibration. A single card thus cut and painted serves to illustrate a ray of plane-polarized light (Fig *A*): two of them placed side by side, with their planes at right angles to each other, *B*, represent the two oppositely-polarized rays produced by a double refracting prism, while two so placed that they mutually cross, represent common light, *C*.

FIG. 11.



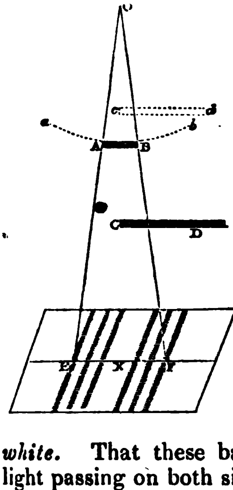
We are now prepared to understand how common light becomes polarized. In the case of the *doubly refracting bodies* the two planes separate, for reasons that will be explained in the next lecture; and as the two waves have the planes of their vibrations at right angles to each other, we see now how the rays are said to be oppositely polarized. As these two waves are propagated with different velocities, they in consequence follow different paths. The *tourmaline* likewise separates the two planes; but it gradually extinguishes the one, by offering such an impediment to its progress that its vibrations are destroyed. The agency of the *reflecting plate* in polarizing light may also be readily accounted for. When a ray of common light falls on a transparent surface, at a certain angle, its planes of vibration are resolved into two, one of which is transmitted, the other reflected; both are polarized, but oppositely.

The action of the *analyzer* or *test* may also be easily understood. Suppose the analyzer to be a *reflecting plate:* if this plate be at the same angle to the ray as the polarizing plate, the vibrations will be reflected when the planes of reflexion of the polarizing and analyzing plates coincide—but will be transmitted (that is not reflected) when the planes are at right angles to each other. Suppose the analyzer to be a *tourmaline* plate: in one position this plate permits the vibrations to be transmitted, but in a position perpendicular to this it destroys them. So that in these two rectangular directions, the crystal of tourmaline must possess unequal elasticities; for the motion or vibration is transmitted in the one, but stifled or destroyed in the other direction. Suppose the analyzer to be a *rhombohedron of Iceland spar;* in either of two rectangular directions the vibrations of the polarized incident ray are propagated unchanged, but at an angle of 45° to either of these positions, the plane of vibration of the incident ray is resolved into two rectangular planes, each of which forms an angle of 45° with the incident ray.

Interferences of Light.—It is a law in dynamics, that the velocity produced by two joint forces, when they act in the same direction, will be as the sum of the forces. Hence if two waves, all of whose parts respectively coincide, meet, it is evident that their velocities will be doubled. Whether the vibrating medium be water, air (*sound*), or ether (*light*), this statement holds good : the intensity of the waves is doubled.

But the velocity of two joint forces, when they act in opposite directions, will be as their differences. Hence, if a wave (of water, air, or ether) be half an undulation behind another wave, the velocities of the two are mutually destroyed. When stones are thrown into a pond, and two groups of waves cross each other on its surface, there are points at which the water remains immoveable when the two systems are nearly of the same magnitude, while there are other places in which the force of the water is augmented by their concurrence. If two sonorous undulations differ a little from each other in frequency, they alternately tend to destroy each other, and to acquire a double, or, perhaps, a quadruple force; and the sound gradually increases and diminishes in continued succession at equal intervals. This alternate intension and remission is called *a beat.*

FIG. 12.



In the same way, the waves of the luminiferous ether interfere, and, mutually destroying each other, cause darkness. This important fact, that under some circumstances, light added to light causes darkness—a fact apparently fatal to the projectile theory of light—was first established by Dr. Young. This distinguished philosopher—whose attainments and knowledge were insufficiently estimated while he was living—passed a sunbeam through a hole (O) made with a fine needle in thick paper, and brought into the diverging beam a slip of card (A B) one-thirtieth of an inch in breadth, and observed its shadow (E F) on a white screen, at different distances. The shadow was divided by parallel bands, but the *central line* (X) *was always white.* That these bands originated in the interference of the light passing on both sides of the card, Dr. Young demonstrated by simply intercepting the light on one side by a screen (C D), leaving the rays on the other side to pass freely. In this arrangement all the fringes which had before existed in the shadow immediately disappeared, although the light inflected on the edge

(A) was allowed to retain its course. The same result took place when the intercepting body was at *C D*, before the edge *B* of the body.

By a series of wooden sliders, originally contrived by Young*, but put into a very convenient form for use in the lecture-room, by my friend Mr. Woodward, the interference of waves may be neatly illustrated. By this apparatus it will be seen that when the difference amounts to 2, 4, 6, or other even number of half undulations, the waves coincide and mutually augment their intensities; while, when the difference amounts to 1, 3, 5, or other odd number of half undulations, there is discordance and mutual destruction. Now it will be perceived, that these numbers coincide with those referred to by Newton, as expressive of his fits of transmission and reflection.

If two waves of *homogeneous* or *monochromatic light* interfere, the result will be *an augmentation* or *diminution* of *brilliancy*, or *complete destruction*. The light is *augmented* when the waves accord—but is *lessened* or *destroyed* when they are mutually opposed. Hence Newton's rings, seen by homogeneous light, are merely dark and light bands of one and the same colour.

But if two waves of *heterogeneous* or *white light* interfere, the result will be *the production of vivid coloured fringes*. Certain colours are destroyed, while others remain, or have their brilliancy augmented.

It is a law in dynamics, that a body acted upon by two forces united, will describe the diagonal of a parallelogram in the same time in which it would have described its sides by the separate action of those forces†. Hence, if two waves, whose molecules are in the same phases of vibration, but whose planes of vibration are more or less angular, say rectangular, to each other, the only effect produced is an alteration of the plane of vibration.

This is an explanation of a fact discovered by Fresnel, and laid down by him as a law, that "two rays of light, polarized at right angles to each other, exhibit none of the phenomena of interference," that is, they produce no colours or fringes.

If both the forces act upon a body in such a manner as to move it uniformly, the diagonal described will be a straight line; but if one of the forces acts so as to make the body move faster and faster, then the line described will be a curve. Now this dynamical law explains how two *plane* luminous waves, whose molecules are vibrating in rectangular planes, by their mutual action, produce a *circular* or *elliptical* wave. For if two systems of waves of equal intensity, and polarized in rectangular planes, differ in their progress ¼ of an undulation, the compound movement which they will communicate to each molecule, instead of being *rectilinear*, as in the two fasciculi considered separately, will be *circular*, and will be performed with uniform velocity. But if the difference of progress, instead of being an even or an uneven number of ¼th of undulations, be a fractional number, the vibratory movements will be neither rectilinear, nor circular, but *elliptical.*

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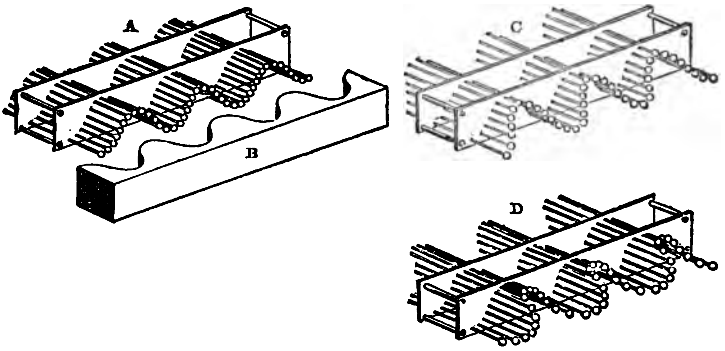
* *Lectures on Natural Philosophy*, vol. i., p. 390, plate xxv., fig. 352 D.

† This fact was demonstrated by a neat machine, invented by Mr. E. M. Clarke, of the Strand.

Here is an apparatus (fig. 13), contrived, I am informed, by Professor Wheatstone, which illustrates how two rectangularly polarized rays of light may influence each other. It consists of a series of rods disposed horizontally in an undulated form, so as to represent a system of plane waves. One end of each rod is rendered conspicuous by a white ball, and it will be seen, that, as now arranged, all the balls (which represent a line of etherial molecules) are in one plane, *A*. If now a block of wood, *B*, cut so as to represent a system of plane waves of equal size to those represented by the rods, be pressed against the balls, so that the two systems of waves act on each other in a rectangular direction, then, when the waves coincide, the plane, in which the balls lie, changes, and becomes diagonal, as in *C;* whereas, if the block be so applied to the balls, that the two systems of waves do not coincide, then the balls no longer remain in one plane, but become placed in a helicoidal manner, representing a circular or elliptical wave, as in *D.*

FIG. 13.



With these remarks I finish the theory of light, and have now arrived at the subject of *Coloured Polarization.*

LECTURE II.

3. COLOURED POLARIZATION.

When an excessively thin film of a doubly refracting crystal is placed in the polariscope, that is, between the *polarizing* and *analyzing* plates, the most gorgeous colour or colours appear, and when the analyzer is rotated on its axis they change to complementary tints. If the film be of uniform thickness, the colour is uniform; but if the film be of irregular thickness, different colours are perceived.

In order to produce colour, it is necessary to use, first, a *polarizer*, as a tourmaline, a doubly refracting prism, or a reflecting plate; secondly, a *film of a doubly refracting crystal*, called the *depolarizer;* and, thirdly, an *analyzer* or *test*, as a tourmaline, a reflecting plate, or a doubly refracting prism.

The office of the *polarizer* is indicated by its name; it polarizes the light. Without this no colour is perceived, for a reason which will be hereafter explained.

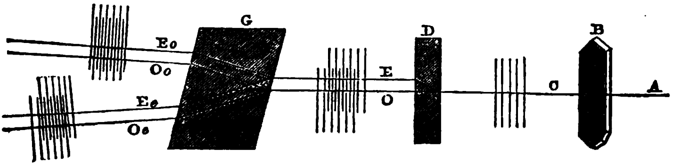
The *doubly refracting film*, called the *depolarizer*, receives the light thus polarized, and doubly refracts it. That is, a system of waves, constituting the incident ray, entering the crystalline film, is resolved into two systems of equal intensities within it. These form respectively the *ordinary* and *extraordinary* rays (fig. 14, *O* and *E*). They are polarized in planes +45° and—45° to that of the incident system, so that the plane of polarization of the ordinary system forms an angle of 90° with that of the extraordinary system.

Now, the two systems of waves thus produced traverse the crystal in different directions and with different velocities; but as the film or plate is excessively thin, they emerge superposed. One set proceeds through the crystal more slowly than the other; or, in the language of a distinguished writer on this subject, one set *lags behind the other:* so that at their emergence they are found to be in different phases of vibration.

By the *analyzer* each of the two systems (*O* and *E*) is resolved into two other systems (*Oo Oe* and *Ee Eo*), so that now four systems or two pairs are produced.

But the vibrations of these four systems are made in two planes: that is, two in one plane, and the other two in a second plane, which is rectangular to the first. Now, as the two vibrations which are made in the same plane, are not in the same phase (the one system having suffered a greater retardation than the other), the waves interfere and produce colour (if the incident light be white). But the two vibrations of the one plane *conspire*, while those of the other plane are *opposed*. Hence the tint or colour produced by the interference of the waves, in one plane, is complementary to that produced in the other plane. So that if the analyzer be a doubly refracting prism, both complementary colours are seen by transmission; but if it be a reflector, one is reflected and the other transmitted; whereas, if it be a tourmaline, one is transmitted, while the other is suppressed, extinguished or stifled.

FIG. 14.



Production of Complementary Tints.

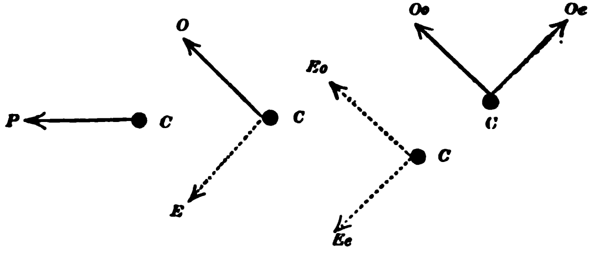
A. A ray of common or unpolarized light incident on *B*.
B. The polarizer (a plate of tourmaline).
C. A ray of plane polarized light incident on *D*.
D. The doubly refracting film or depolarizer.
E. The extraordinary ray } produced by the double refraction of the ray *C*.
O. The ordinary ray
G. The analyzer (a doubly refracting prism).
Eo. The ordinary ray } produced by the double refraction of the extraordinary ray *E*.
Ee. The extraordinary ray
Oo. The ordinary ray } produced by the double refraction of the ordinary ray *O*.
Oe. The extraordinary ray

To render somewhat more intelligible the cause of the colours being complementary, and, therefore, to explain what is meant by the *conspiration* and *opposition* of vibrations, let us suppose the vibrations of the polarized light (*C*, fig. 14) to be made in the plane, *C P*, fig. 15; and to give more precision to our ideas, let us further suppose that the molecule *C* is, at a given instant, moving *from C* towards *P*.

The doubly refracting film resolves this motion into two other motions, performed at right angles to each other, one in the direction *C O*, the other in the direction *C E*. The waves produced by the vibrations in the plane *C O*, we shall suppose to constitute the *ordinary* system, while those in the plane *C E* form the *extraordinary* system. But the plate is much too thin to have produced between these two systems any sensible separation.

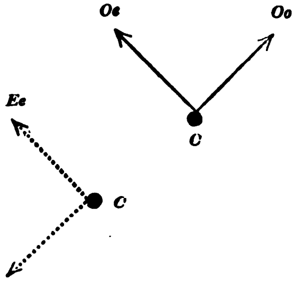
Each of these motions is resolved, by the analyzer, into two others at right angles to each other. That is, the vibration *C O* is resolved into the vibrations *C Oo* and *C Oe;* while the vibration *C E* is resolved into the vibrations *C Eo* and *C Ee*. Now, it is obvious, that the two motions *C Oo* and *C Eo* act in the same direction, or, in other words, they *conspire*, or *strengthen each other;* while the motions *C Oe* and *C Ee*, though performed in the same plane, *oppose* or *destroy* each other.

Fig. 15.



By rotating the analyzer the reverse happens: *C Oo* and *C Eo* ***oppose*** or ***destroy*** each other, while *C Oe* and *C Ee* ***conspire***, or ***strengthen each other***, as in fig. 16.

Fig. 16.



Thus, then, the original polarized ray (*C*, fig. 14) has been resolved into four rays, two polarized in one plane, and the other two polarized in a plane rectangular to this. The two rays which interfere and destroy each other, differ by half an undulation. The colour produced by the interference of the *conspiring* rays, corresponds to the difference of the routes of the two polarized rays in the plate or film, while that which results from the interference of the *opposing* rays, is that which is due to the same difference augmented or diminished by half an undulation. In the case above noticed, in which *C O e* and *C E e* (fig. 15) are opposed, the colour corresponds to the difference *plus* half an undulation.

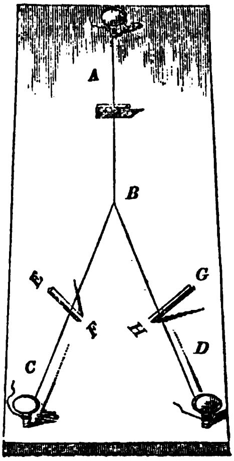
But it may be asked, What is the use of the polarizing plate? What is the reason that no colour is perceived if the light which is incident on the double refracting film be common or unpolarized? To explain this, let us suppose that a ray of common or unpolarized light consists of two rays rectangularly polarized. Each of these rays will suffer the same series of divisions, subdivisions, and interferences as the former; but the tints produced by the one ray will be complementary to those of the other; so that we shall thus obtain two pairs of complementary tints, and as the tints of each pair will emerge superposed, they will neutralize each other, and the resulting light will be of uniform whiteness.

Thus,	1st PAIR OF TINTS.		2d PAIR OF TINTS.
Suppose the two complementary tints produced by one ray to be....................................	Green	and	Red.
Those produced by the second ray will be	Red	"	Green.
And the sum of each pair will be	White.		White.

For red and green are complementary tints, and produce by their union white light, as I have already demonstrated.

The office of the doubly refracting film, called the depolarizer, is to doubly refract the polarized light. It prepares the rays for the changes which they have ultimately to undergo and by which colour is to be produced. The thickness of the film or crystalline plate determines the tint; but the actual thickness required to produce a given tint depends on the nature of the crystal. By this plate or film two rectangularly polarized systems of waves are produced, which traverse the plate in different directions and with different velocities, and emerge in different phases of vibration. Now as they are superposed, and as the retardation amounts only to a few undulations and parts of an undulation, it might be supposed that colour would be produced by their interference. But I have already stated that two rectangularly polarized rays do not interfere, so as to produce colour. In order, therefore, to make them interfere, their planes of polarization must be made to coincide; and to do this is the function of the analyzer.

FIG. 17.



In order to assist us in comprehending how a polarized ray may be resolved into two others polarized in different planes, we may take, as an illustration, a stretched cord, fig. 17 *A B*, dividing at *B* into *B C* and *B D*, making a small angle with each other at *B*, and having either equal or unequal tension. Let us suppose the extremity *A* of the single cord to be made to vibrate regularly in either a horizontal or vertical plane; now, by means of two polished guiding-planes, *E F* and *G H*, inclined at different angles to the horizon, and making a right angle with each other, the horizontal vibrations of the cord *A B*, will give rise to two other vibrations, parallel respectively to *E F* and *G H.* And if we assume the two branches *B C* and *B D* to be unequally tense, the waves produced by the vibration of *A B* will be propagated along them with unequal velocity. So that this illustration, which I have adopted from Sir John Herschel's able treatise on light, serves to explain not only how a vibration in one plane may be resolved into vibrations in two other planes, but also why the two resulting waves are propagated with unequal velocity.

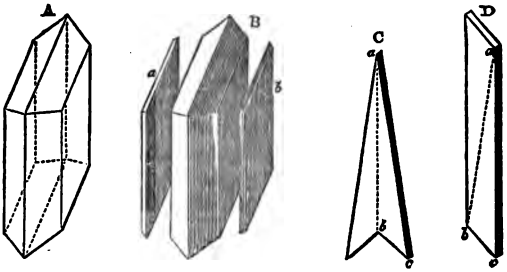
Though a thin plate of Iceland-spar or of any other doubly refracting crystal serves, when placed in the polariscope, for the production of colour; yet certain crystals are preferable to others on account of the facility with which they may be split into thin laminæ. Selenite and mica are especially convenient for this purpose; and the former of these is extensively employed by opticians in the preparation of a variety of beautiful and ingenious polariscope illustrations. On this account a brief notice of it is requisite.

Selenite, or *sparry-gypsum*, is the *native crystallized hydrated sulphate of lime* ($Ca\,O.\ S\,O_3+2$ Aq.) It occurs imbedded in London clay. It is found also at Shotover Hill, near Oxford, where the labourers call it *quarry glass*, and likewise at the Isle of Sheppy. Very large crystals of it are found at Montmartre, near Paris. The crystalline forms in which it occurs belong to the oblique rectangular prismatic system. Haüy and the late Mr. William Phillips describe its primary form as a right oblique-angled prism; so that the lateral faces of the crystal are regarded by them as the terminal planes. But the optical characters of the crystal prove the incorrectness of the description of these celebrated mineralogists: and here, I would observe, is an excellent illustration of the great value of polarized light to the crystallographer. In this particular instance it enables him to distinguish a lateral face, from a terminal plane, of a prism.

The crystals of selenite which are most frequently met with, are oblique rectangular prisms, with ten rhomboidal faces, of which two are considerably larger than the others (fig. 18 *A*). They are very easily slit into thin laminæ (*a b*, fig. 18 *B*), parallel to these larger lateral faces (terminal planes of Haüy and W. Phillips).

Macles or hemitrope crystals of selenite are very common. By hemitrope, a word derived from the Greek (from ἡμι *half*, and τρέπω *I turn*), is meant a figure produced by cutting the primary crystal in two, causing one of the fragments to make half a revolution, and then uniting the sides actually in contact. The most singular and common hemitrope variety of selenite is that called *arrow headed selenite* (fig. 18 *C*), and which is so called because the crystal is formed like the barbed head of an arrow. Its nature may be easily explained. Cut a card or thin board in a rhomboidal form to represent one of the laminæ taken from lateral faces of the prism (fig. 18 *D*). Then divide it in the direction of its greater diagonal (*a b*), and transpose the separated parts in such a manner, that two of the alternate angles, produced by the diagonal division, shall make the point —the other two, the barbs—of the arrow-head.

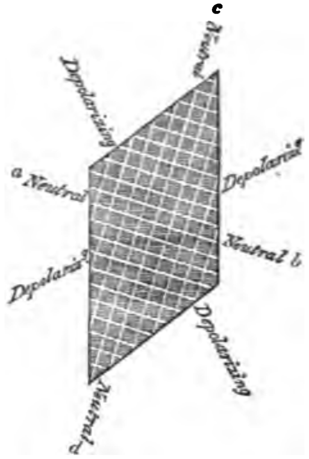
FIG. 18. *Selenite.*



The optical structure of films or thin plates of selenite, having a thickness of from $\frac{1}{20}$th to the $\frac{1}{60}$th of an inch, is very curious. In two rectangular directions they allow perpendical rays of polarized light to traverse them unchanged: these directions are called the ***neutral axes.*** In two other directions, however, which form respectively angles of 45° with the neutral axes, these films have the property of double refraction. These directions are usually denominated ***depolarizing axes;*** but they might be more correctly termed ***doubly refracting axes.***

In order to render these properties more intelligible, suppose the structure of the film to be that represented by fig. 19, in which the film is seen to be crossed by two series of light lines, or passages, the one perpendicular to the other. These are to represent the ***neutral axes.*** We may imagine, that in these directions only can the ethereal molecules vibrate. A ray of incident polarized light whose vibrations coincide with either of these lines, is transmitted through the film unchanged. But a ray of incident polarized light whose vibrations form an angle of 45° with these lines, or, in other words, which coincide with the diagonals of the square spaces, suffers double refraction; that is, it is resolved into two vibrations, one parallel with *a b*, the other parallel with *c d*, and, therefore, the directions of the diagonals of the squares are called the ***doubly refracting*** or ***depolarizing axes.*** But the two resulting vibrations are not propagated, in these two rectangular directions, with equal velocity, the one suffering greater retardation than the other, so that the waves, at their emergence, are in different phases of vibration, though they do not interfere

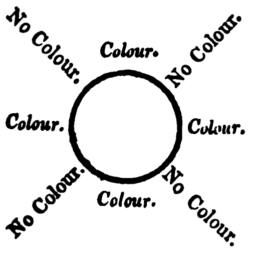
FIG. 19. *Imaginary Structure of a Plate of Selenite.*



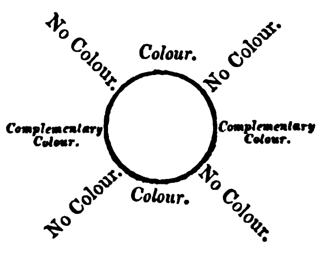
so as to produce colour, because their planes of vibration are rectangular. By the analyzer, however, their planes are made to coincide, and colour is produced; and on rotating the analyzer on its axis, the colour changes and becomes complementary.

To illustrate these statements, place a film of selenite, of uniform thickness, in the polariscope. On rotating the film (the analyzer and polarizer remaining still), a brilliant colour is perceived at every quadrant of a circle, but in intermediate positions it vanishes altogether. We observe, however, that the tint does not change, but only varies in intensity. If, now, the film be fixed and the analyzer rotated, we also observe colour at every quadrant of a revolution; but the tint changes and becomes complementary at every quadrant—the same tint reappearing at every half revolution: so that when the film alone is revolved one colour only is seen, but when the analyzer alone is revolved, two colours are seen.

Effect of revolving the film of Selenite.



Effect of revolving the Analyzer.



If we employ, as the analyzer, a double refracting prism, we observe two complementary disks of colour, and these may be made to cross and produce white light as before shown.

The thickness of the film of selenite determines the particular tint. If, therefore, we use a film of irregular thickness, different colours are presented by different thicknesses. A wedge-shaped piece will produce parallel bands of colours, and two wedges crossed present diagonal bands. A plano-concave film, as well as a plano-convex film, gives concentric rings of colour, the former with a black, the latter with a white, centre.

Two films superposed, do not give the colour which would arise from the mixture of the two colours, but either the colour which corresponds to the joint thickness of the films, or that which belongs to the difference of their thickness. When the two films are put together, as they lie in the crystal, the resulting colour depends on the *sum* of the thicknesses. But when the two films are crossed, so that similar lines in the one are at right angles to similar lines in the other, the resulting tint depends on the *difference* of the thicknesses. These facts admit of very beautiful, curious, and interesting illustrations. Thin films of selenite of uniform thickness are so arranged as to slide over figures also formed of films of selenite. The changes of colour effected in the tints are most striking, and to unphilosophical minds almost magical.

In the opticians' shops are met with a great variety of devices prepared with films of selenite of different thicknesses, and which constitute philosophical toys illustrative of the before-mentioned facts. *Gothic windows, stars, flowers, fruits, animals* (butterflies, parrots, dolphins, and chameleons), and *theatrical figures* (Jim Crow, harlequin, &c.), are some of the ingenious, and often laughable illustrations contrived by Mr. Darker.

Test of Double Refraction.—From the preceding statements then, it appears, that the polariscope becomes a very delicate test of double refraction. A very large number of crystalline, and other bodies, possess a doubly refractive property; but comparatively few of these have it in so high a degree as to present, under ordinary circumstances, the phenomenon of double images; that is, the separation of the two systems of ethereal waves is not, in general, sufficiently great to be visible to the eye. In such cases, therefore, the polariscope is of great value, since it enables us to detect the slightest degree of double refraction. Some doubly refracting bodies present, in the polariscope, most gorgeous colours, as selenite. Others, however, which possess the doubly refractive property in a much slighter degree, require the aid of a thin film of selenite, of uniform thickness. Their double refractive property then becomes evident by the change which they induce in the colour of the film. Without this, we see light or dark fringes or bands, or black or white crosses, but no colour.

Cause of Double Refraction.—Being now in possession of an exceedingly delicate test of double refraction, we are prepared to enter into an inquiry into the cause of this property.

Now we shall find that every body endowed with equal elasticity in every direction, is a single refractor. Alter its elasticity in any one direction, put it in a state of unequal tension, and immediately it acquires the property of double refraction. Hence then, double refraction may be temporarily or permanently communicated to bodies, by temporarily or permanently disturbing the equality of their elasticity in different directions.

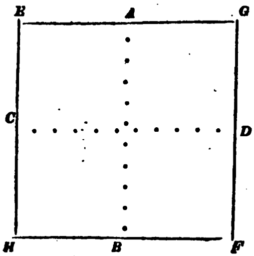
1. *Pressure produces double refraction.*—In fluids (gases and liquids) pressure is equally distributed in all directions, which is obviously owing to the facility with which the molecules shift their places. Hence pressure on fluids does not communicate to them the power of double refraction.

In solids, however, matters are far otherwise. Owing to cohesion, the molecules cannot change their relative positions; and, therefore, in this form of matter unequal degrees of tension may exist in different directions: so that pressure may be communicated in any desired direction without being equally or uniformly distributed.

Now a transparent solid, as a well-annealed piece of glass, all of whose parts possess equal elasticity, is a single refractor; but if we subject such a body to the influence of a compressing force, it becomes a double refractor, and acquires neutral and doubly refracting (depolarizing) axes; the former parallel and perpendicular to the direction of pressure, the latter 45° inclined to them.

Let us consider for a moment what must be the effect of pressure in any given direction. Suppose a rectangular piece of glass (fig. 20) to be subjected to pressure in the direction $A\ B$: the immediate effect will be to urge the contiguous particles nearer together in this direction, and thereby to call into action their repulsive forces. But it will also urge the particles asunder in the direction $C\ D$,—that is, in a direction perpendicular to that of the pressure, and thereby to call into operation their attractive forces. Thus then, it is obvious, that a force, which when applied to a solid, causes a condensation in the direction of the force ($A\ B$), is attended with dilatation or expansion in a direction perpendicular

FIG. 20.



to it (*C D*). In the first direction the elasticity is a maximum—in the second direction it is a minimum. Incident light polarized in a plane parallel with either of these directions passes through unchanged, and these directions are called the ***neutral axes.*** But if it be polarized in a plane inclined 45° to either of these directions (that is, in the direction *E F* or *G H*) it is resolved into two systems of waves, one polarized in the direction *A B*, the other in the direction *C D*. The directions *E F* and *GH*, are, therefore, the ***doubly refracting*** or ***depolarizing axes.*** But the system polarized in the plane *A B*, will proceed more slowly (owing to the maximum elasticity in that direction) than the system *C D* (which is polarized in the direction of the minimum elasticity). Hence, at their emergence, the two systems of waves are in different phases of vibration, but they do not interfere so as to produce colours, owing to the plane of vibration of the one being rectangular or perpendicular to that of the other. When, however, we apply the analyzer, and restore these two rectangular planes to a common plane, interference takes place and colour results.

Let us now take the case of a flexed body. When I bend a cane or other solid, the convex surface is in a state of expansion or dilatation, while the concave surface is compressed. The molecules on the convex surface are urged asunder, and their attractive forces called into operation, while those on the concave surface are pressed together, and their repulsive forces brought into action. Between these two oppositely affected surfaces, there is a neutral line where equilibrium exists, and on both sides of this the degree of strain augments as we recede from the line. Now, if a well annealed, and, therefore, single refracting plate of glass be bent, and examined while in the polariscope, it will be found to have acquired, while in the bent state, double refracting properties. Two sets of coloured fringes are perceived, one on the convex or dilated side of the plate, and the other on the concave or compressed side. Between these two sets of fringes is a black line, indicating the situation where neither compression nor dilatation exists, and where, therefore, double refraction is absent.

Thus then the polariscope becomes a valuable means of detecting the existence of unequal tension or strains in transparent bodies, and Dr. Brewster has suggested its useful application to the determination of the intensity and direction of all the forces which are excited by a superincumbent load in different parts of the arch, as also the intensity and direction of the compressing and dilating forces which are excited in loaded framings of carpentry. For these purposes, models in glass or copal are to be prepared, and the effects are rendered visible by exposing the models to polarized light. He has likewise constructed a *chro-*

matic dynamometer for measuring the intensities of forces, founded on the facts already stated. It consists of a bundle of narrow and thick plates of glass, fixed at each end in brass caps. Then when any force is applied to a ring in the middle of the plates, the ends being fixed, the plates of glass will be bent, and the force thus produced is measured by the tints that appear on each side of the black line.

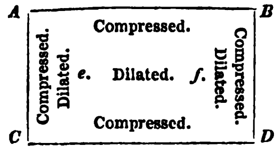
By the gradual induration, as well as by the mechanical compression and dilatation of animal jellies, fringes may be produced, as in glass.

2. *Unequal heating causes double refraction.*—When heat is applied to bodies, it causes them to expand or dilate. If the substance to which the heat is applied be a bad conductor, the part in contact with the heated body becomes hot, and expands before heat is communicated to the neighbouring parts. Hence the bad conductor endeavours to curve, just as when we hear a compound bar of iron and brass, a curvature is induced, owing to the unequal expansile power of these two metals, and as the brass expands more than the iron, the latter forms the inner or concave side of the curved bar, while the brass forms the outer or convex side. On this principle is constructed the compensation balance of a watch.

Glass is a bad conductor of caloric, and when a heated body is applied to it, the part in contact with this becoming hot, expands, but owing to the bad conducting quality of the medium, the surrounding parts not being influenced by the heat, do not expand, but resist the dilatation of the heated portion. In this way, therefore, the immediate effect of heat on one part of a piece of glass, is to put all the surrounding parts into a strained state, one part is expanding, and other parts are resisting the dilatation. When the difference of temperature is extreme, the violence of the strain is such that very thick pieces of glass are sometimes rent asunder.

It is very desirable that we should be acquainted with the precise mechanical condition of the glass thus partially subjected to caloric. A knowledge of this would greatly assist us in comprehending the optical phenomena. But the subject is replete with difficulties. Perhaps, some assistance may be obtained from the following considerations:—

FIG. 21.



Let *A B C D* (fig. 21), be a rectangular plate of glass, subjected to heat along its edge, *A B*. This portion of the glass being heated, tends to expand; but on account of its connection with other portions of the glass, cannot do so without forcing these to participate in its augmented bulk. These, however, owing to the bad conducting power of the glass, retain their original temperature, and consequently refuse to expand, so that the stratum is subjected to compression; that is, it is prevented from acquiring that volume which is natural to it, in this heated state. The central stratum *e f*, is in a state of dilatation or expansion, owing to its particles being urged asunder by the tendency of the upper stratum, *A B*, to expand. The resistance offered to the expansion by *e f*, tends to produce pressure on the lower stratum *C D*, the particles of which will be urged together. This lower stratum *C D*, like the upper one *A B*, will then be in a state of compression. As the tension of *e f* is sustained at *A B* and *C D*, it will tend to send inwards the lateral columns *A C* and *B D*, dilating them at the convex portion of the bend, and compressing them at the concave portion. By these strains, therefore, the rectangular plate of glass will assume a figure concave on all its edges.

It is obvious then, from the unequal states of tension of the different parts of a piece of glass thus partially heated, that it ought to acquire doubly refracting properties, and the polariscope shows that it does so. In this state, the glass exhibits distinct *neutral* and *doubly refracting* (*depolarizing*) *axes*, the neutral ones being parallel and perpendicular to the direction in which the heat is propagated. The black fringes, sometimes called lines, of no polarization, indicate the neutral axes, or those portions of the glass which are destitute of the property of double refraction.

It deserves especial notice that fringes make their appearance in the part of the glass most distant from the heated body, before they have received any sensible accession of heat, and which, therefore, must depend on the state of strain into which they are thrown by the effect of the heat on the other parts of the mass, in the way I have already endeavoured to explain.

Dr. Brewster has suggested the construction of two kinds of *chromatic thermometers*, for measuring changes of temperature by the production of coloured fringes, exhibited by glass plates when exposed to heat; for "every tint in the scale of colours has a corresponding numerical value, which becomes a correct measure of the temperature of the fluid." In the one instrument, the tints originate immediately from the changes of temperature; in the other, they are produced by the difference of pressures upon the glass, occasioned by the difference of expansions arising from changes of temperature. I must refer you to his paper in the *Philosophical Transactions* for 1816, for details respecting them.

3. *Unequal cooling causes double refraction.*—If a piece of

hot glass of uniform temperature be unequally cooled, as by placing one of its edges on a cold mass of iron, it acquires doubly refracting properties, and when examined by polarized light, presents fringes, &c. similar to those observed in glass unequally heated. It is obvious, however, that as the physical condition produced by cold is diametrically opposite to that caused by heat, so the structure of the corresponding parts of the two glasses (the one which has been cooled, and the other which has been heated) must be opposite.

4. *Unannealed glass is a double refractor.*—If glass be suddenly cooled after having been melted, it possesses certain remarkable properties, which unfit it for ordinary use. Sometimes it splits or flies to pieces in the act of cooling; or if it fail to do this, a very moderate change of temperature, a slight external force, a scratch, or a slight fracture, is sufficient to cause it to crack and fly to pieces. The glass tears called *Rupert's drops*, or *hand-crackers*, and the *proofs*, or *philosophical phials*, are familiar illustrations of this kind of glass. In order to prevent it acquiring this remarkable condition, glass, after being fashioned, is submitted to the process called *annealing*, that is to very slow cooling in the annealing oven or lier. Glass which has undergone this process is said to be *annealed*, while that which has not is termed *unannealed*. But the so-called unannealed glasses sold by the opticians are in fact annealed glasses, which have been reheated until they begin to soften, then cooled by placing them on the ashes beneath the furnace, and afterwards ground and polished.

The optical properties of unannealed glass are very remarkable. To comprehend them let us consider the mechanical condition of the glass. When a mass of red-hot and soft glass is exposed to a cool air, its external portion becomes cold and rigid, while the inner parts are still hot and soft. After a short time, however, the latter solidify and cool, but are prevented from contracting themselves into the smaller bulk which is natural to them in their cooled state, by the rigid crust, which acts like an arch or vault, and keeps them distended, but which is to a certain extent strained and drawn somewhat inwards by the tension exercised on it by the internal parts. It is obvious then that the different parts of a mass of unannealed glass are unequally and differently strained; the internal being in a state of distention or dilatation, the external in that of compression. So that the state of the different parts, and the distribution of the forces, will be almost exactly similar to those already described, in the case of annealed glass which has been unequally heated. "The analogy between the cases," says Sir John Herschel, "would be complete, if, instead of supposing the annealed plate heated at one edge only, the heat were applied to all the four simultaneously, by surrounding it with a frame of hot iron."

There is one very important point in reference to these unannealed glasses, to which I must beg your attention; I refer now to the circumstance that in them, *the polarizing* (doubly refracting) *structure depends entirely on the external form of the glass plate*, and on the mode of aggregation of its particles. This will be very obvious by observing the different shapes of the fringes respectively presented by square, circular, oval, rectangular, and other shaped plates. The circular and square plates have only one axis of [no] double refraction; whereas the oval and rectangular plates have two axes. By dividing and subdividing these plates, the doubly refractive property is not only greatly diminished, but sometimes even destroyed, if the portion be very small. Moreover, it is distributed in a new manner, according to the shape of the fragment. The dissected unannealed glasses, sold in the opticians' shops, beautifully illustrate the dependence of the form of the coloured fringes on the external shape of the glass. Thus the pattern produced by one circular piece of unannealed glass, is very different to that of a circle formed by joining four segments.

In these particulars, the unannealed plates of glass differ very widely from doubly refracting crystals. The fringes and colours, presented by the latter, are unaltered by the changes we may effect in the external form of the crystal—the smallest fragment producing the same system of fringes as the largest; and, provided the thickness remains the same, the polarizing force suffers no diminution by the reduction in size.

We are then constrained to infer that the optical properties of crystals are those of their integrant molecules; while those of the unannealed glasses depend on the mode of arrangement of the molecules, and on the external form of the mass.

The effects produced by superposing similarly shaped pieces of unannealed glass are striking, and, at first, surprising; but, on consideration, may be easily understood. If they be symmetrically superposed, similar points being laid together, the tints will be equal to the sum of the separate tints:—but, if superposed crosswise, the resulting tints will be the difference of the separate tints. This may be conveniently shown by causing an unannealed glass bar to rotate in front of another unannealed bar.

Applications.—These facts respecting the properties of unannealed or imperfectly annealed glasses, admit of some valuable practical applications. To the optician it is of the highest importance that the glass, of which lenses and prisms are made, should possess uniform density, and be free from all defects arising from irregularities in the annealing process. To detect these the glass should be carefully examined by polarized light previous to being ground and polished; and by this agent the slightest defects are made appreciable.

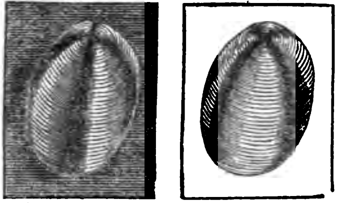
So also glass vessels employed for domestic purposes may be advantageously tested by the same agent. The facility with which tumblers, &c. crack, sometimes spontaneously, at other times while in the hands of the glass-cutter, or when warm water is poured into them, or when exposed to a slight blow, depends on some imperfection in the annealing process. Hence, also, the reason why *run glass* (that is, glass made without paying the duty) is very apt to crack; for owing to the rapidity with which all the stages of its manufacture have been hurried on, it is not well made, and sufficient time has not been allowed for the annealing process.

It is probable, also, that manufacturers, or rather the mounters of electrical machines, might beneficially avail themselves of polarized light in the selection of glass cylinders and plates. Recently made cylinders, when mounted, will sometimes crack, or fly, as it is termed, without any obvious agency, owing, I presume, to some defect in the annealing process, which, perhaps, might have been previously discovered by means of polarized light.

An argument in favour of the vegetable origin of the diamond has been founded by Dr. Brewster, on the phenomena presented by this substance, when examined by means of polarized light. It is well known that various opinions have been held by different writers on the mode of formation of this mineral. All of them, however, may be included under two divisions: those which assume the diamond to be the direct produce of heat on carbonic acid or carbon, and those which ascribe it to the slow decomposition of plants. Dr. Brewster, who adopts the latter notion, met with a diamond which contained a globule of air, while the surrounding substance of the diamond had a polarizing (doubly refracting) structure, displayed by four sectors of polarized light encircling the globule. He, therefore, inferred that this air bubble had been heated, and by expansion had produced pressure on the surrounding parts of the diamond, and thereby communicated to them a polarizing structure. Now for this to have happened, the diamond must have been soft and susceptible of compression. But as various circumstances contribute to prove that this softness was the effect of neither solvents nor heat, he concluded that the diamond must have been formed, like amber, by the consolidation of vegetable matter, which gradually acquired a crystalline form by the influence of time and the slow action of corpuscular forces.

Starch grains have a laminated texture, and possess a doubly refractive power. They are composed of concentric layers of amylaceous matter. On some part of the surface of each grain is a circular spot, called the *hilum*. This appears to be an aperture or transverse section of the tube or passage leading into the interior of the grain, and by which the amylaceous matter, forming the internal laminæ, was conveyed. On examining the grains by the polarizing microscope, unequivocal evidence of their doubly refractive power may be obtained. At least I have found this to be the case in all the starches which I have yet examined, viz., *tous les mois*, potato-starch, West Indian arrow-root, sago-meal, Tahiti arrow-root (obtained from a species of *Tacca*), tapioca-meal, East Indian arrow-root (*Curcuma angustifolia*), wheat-starch, Portland arrow-root (*Arum maculatum*), and rice-starch. The larger grained starches form splendid objects for the polarizing microscope; *tous les mois* being the largest may be taken as the type of the others. It presents a black cross, the arms of which meet at the hilum. On rotating the analyzer the black cross disappears, and at 90° is replaced by a white cross; another, but much fainter black cross, being perceived between the arms of the white cross. Hitherto, however, no colour is perceptible. But if a thin plate of selenite be interposed between the starch grains and the polarizer, most splendid and gorgeous colours make their appearance. The arms of the cross acquire the colour which the selenite plate yields in polarized light. The four spaces between the arms also appear coloured; but their tint is different to that of the cross. The colours of the first and the third spaces are identical, but different to those of the second and fourth, both of which have the same tint. At the point where the colours of the arms and of the interspaces meet, the tints blend. All the colours change by revolving the analyzer; and become complementary at every 90°.

A. Fig. 22. *B.*



Grains of Tous les Mois viewed by the Polarizing Microscope. ***A.*** **represents the appearance when the planes of polarization of the polarizer and analyzer are at right angles to each other;** ***B.*** **when they coincide**

The appearances presented by potato-starch are similar to those of *tous les mois*. Several other starches (as West Indian arrow-root, sago-meal, Tahiti arrow-root, tapioca-meal, and East Indian arrow-root) present black and white crosses, and, when a selenite plate is used, also colours; but in proportion as the grains are small, are their appearances less distinct. I have not hitherto detected the black and white crosses in wheat-starch, Portland arrow-root, and rice-starch. Their double refractive power, however, is proved by the change they effect in the colour yielded by a plate of selenite.

A great variety of animal structures possess a doubly refracting or depolarizing structure, as a quill cut and laid out flat on glass, the cornea of a sheep's eye, a piece of bladder, gold-beaters' skin, human hair, a slice of a toe or finger nail, sections of bones, of teeth, &c. The crystalline lenses of animals also possess this property in a high degree, owing to their central portion being denser and firmer than the external portion. If the lens of a cod-fish be placed in a glass trough of oil or Canada balsam, it presents twelve luminous sectors separated from each other by a black cross. Even living animals present double refracting properties. The aquatic larvæ of a gnat, commonly called *skeleton larvæ*, form a very amusing exhibition. They are to be placed in water in a very narrow water-trough. In certain positions, they give no evidence of double refraction, but in others, and especially when they are exerting much muscular energy, they possess it in a very marked degree.

LECTURE III.

DOUBLY REFRACTIVE AND OTHER ALLIED PROPERTIES OF CRYSTALS.

In my last lecture I explained the nature and cause of double refraction; and I now proceed to examine the double refractive property of crystals, and to show how this is connected with, or related to, other properties of crystalline substances.

1. *Double Refraction of Crystals.*—Every transparent crystalline body refracts the rays of light which are incident on it at oblique angles; and the degree of its refractive power depends on two circumstances; viz., the angle of incidence, and the nature of the crystalline substance. In these respects crystals agree with all other transparent media.

But a very large number of crystals possess the property of double refraction; and they are, therefore, called *doubly refracting crystals*, to distinguish them from others which have not this property, and which are denominated *singly refracting crystals*.

The double refraction of some crystals is immediately manifested by the production of duplicate images; either through two parallel surfaces, as Iceland spar, or through two surfaces which are more or less inclined on each other. Thus to observe the double refraction of a crystal of quartz, it is necessary to look through a pyramidal and lateral plane at the same time. By this contrivance the surface of emersion is inclined to that of admission, which causes the two pencils to emerge at different inclinations, and so become further separated as they proceed.

Many crystals, however, possess the property of double refraction in so feeble a degree that it is impossible to see, under ordinary circumstances, two images; and in such cases we are constrained to employ the polariscope to detect this property.

In every doubly refracting crystal there are one or more positions or directions in which the two images become superposed;

or, in other words, in which no double refraction exists or is evident. These directions are called the *optic axes* or *the axes of double refraction*. I have already stated that the phrase *axes of* NO *double refraction* would be more intelligible. These axes may be regarded as positions of equilibrium where certain forces, which exist within the crystal and act in opposition, balance each other. In crystals of certain forms they coincide with the geometrical or crystallographical axes, whereas in crystals of other shapes they do not; but to these points I shall again have to beg your attention.

If we consider doubly refracting crystals in regard to the number of their optic axes we may divide them into two orders; one including those that possess only one axis, and another comprehending such as have two axes. The first are called *uniaxial*, the second *biaxial* crystals. As this distinction is connected with other remarkable optical peculiarities, as well as with the geometric and thermotic properties of crystals, it will be necessary to notice it a little more in detail.

a. Uniaxial Crystals.—Those crystals which have only one axis of [no] double refraction, and which, in consequence, are termed *uniaxial crystals*, or *crystals with one optic axis*, belong to the square prismatic or rhombohedric systems. In them the geometric or crystallographic axis is coincident with the optical one; that is, the line or direction in the crystal, around which the figure is symmetrically disposed, or about which every thing occurs in a similar manner on all sides, is coincident with the optic axis, or the axis around which the optical phenomena are the same in all directions. You must not, however, suppose that the axis is a single line; for there must be as many axes as there may be lines parallel to each other, so that the word is merely synonymous with a fixed direction.

In all other directions but the one called the optic axis, these crystals doubly refract; and of the two rays thus produced, one follows the ordinary laws of simple refraction, and is accordingly called the *ordinary ray*, while the other, being subject to an extraordinary law, is denominated the *extraordinary ray*.

These two rays advance with unequal degrees of velocity; the one suffering greater retardation than the other. When the *ordinary* ray advances more rapidly than the extraordinary one, the crystal is said to have a *negative* or *repulsive axis of* [*no*] *double refraction*; but when the ordinary ray advances less rapidly, the crystal is said to possess a *positive* or *attractive axis* In other words, when the extraordinary ray is refracted *towards* the axis, the crystal is said to have a *positive* axis; but when the ray is refracted *from* the axis, the crystal is said to have a *negative* axis. These terms are not very expressive of the property they are intended to represent. Biot used the terms *attractive* and *repulsive* to designate the attractive or repulsive forces which he supposed to emanate from the axes of crystals. For it is obvious that if the extraordinary ray be most retarded, it will be refracted from the axis, that is, it will appear to be repelled by a force emanating from the axis; whereas, if it be the least retarded, it will be refracted towards the axis, or will appear to be attracted by a force emanating from the axis. Now it was to obviate the hypothesis which these terms involve, that Brewster substituted the words *positive* and *negative* for the terms *attractive* and *repulsive*, merely meaning to denote by them the opposition, but not the nature, of the forces.

Table of Uniaxial Crystals.

Negative (—) *or repulsive Crystals* (Extraordinary ray most retarded).	*Positive* (+) *or attractive Crystals.* (Ordinary ray most retarded).
Iceland Spar	Zircon
Tourmaline	Quartz
Nitrate of Soda	Oxide of Tin
Bicyanide of Mercury	Ice

In uniaxial crystals the position of the optic axis is constant, whatever be the colour of the light; whereas in biaxial crystals this is not the case, as I shall presently show.

b. Of Biaxial Crystals.—A very large number of crystals, including all which belong to the right rhombic prismatic, oblique prismatic, and doubly oblique systems, have two axes of double refraction, which are more or less inclined to each other. Such crystals are, in consequence, denominated ***biaxial crystals***, or ***crystals with two optic axes.*** In them there is no single line or axis around which the figure is symmetrical, as in uniaxial crystals; and the optic axes do not always, or even frequently, coincide with any fixed line in the crystals. Now this fact has led Dr. Brewster to believe that the optic axes are not the real axes of the crystals, but only the resultants of the real, or ***polarising***, ***axes***, or lines, in which the opposite actions of the two real axes compensate each other. Hence he terms them the ***resultant axes***, or ***axes of no polarization***, or ***of compensation.***

The following is a list of a few biaxial crystals; and for a more extensive one I must refer my auditors to Dr. Brewster's works:

Table of Biaxial Crystals.

	*Character of Principal Axes**.	*Inclination of Resultant Axes.*
Glauberite	Negative	2° or 3°
Nitrate of Potash	Negative	5° 20′
Carbonate of Lead	Negative	10° 35′
Arragonite	Negative	18° 18′
Borax	Positive	28° 42′
Sugar	Negative	50°
Selenite	Positive	60°
Rochelle Salt	Positive	80°

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* The *principal axis* is, according to Dr. Brewster, the middle point n the two nearest poles of no polarization.—*Phil. Tans.*, 1818.

Of the two rays produced by the double refraction of biaxial crystals, neither can be strictly denominated the *ordinary* one, since neither of them is refracted according to the ordinary law of single refraction. Both of them then are *extraordinary* rays, since they are refracted according to the laws of extraordinary refraction.

Another peculiarity of biaxial crystals is that the position of the optic axes is not constant, but varies in the same crystal, according to the colour of the intromitted ray, and the temperature of the crystal. Thus a violet ray is separated into two pencils when incident in the same direction in which a red one is refracted singly. Sir John Herschel, to whom we are indebted for this discovery, found that the inclination of the resultant axes, in Rochelle salt, is for violet light 56°, and for red light 76°, but in the case of nitre, the inclination of the axes for violet light is greater than for red light, and Dr. Brewster discovered that glauberite has two axes for red light inclined about 5°, and only one axis for violet light. The changes produced on the inclinations of these axes by heat, I shall hereafter have occasion to notice.

In conclusion, then, crystals considered with respect to their singly or doubly refractive properties may be thus arranged :

OPTICAL CLASSIFICATION OF CRYSTALS.

CLASS 1. **Singly refracting crystals.**			
CLASS 2. **Doubly refracting crystals ..**	*Order* 1. Uniaxial.. *Order* 2. Biaxial ..	either	*a.* Repulsive (negative) or *b.* Attractive (positive)

2. *Form of Crystals.*—A remarkable connexion exists between the optical properties and the geometrical forms of crystals ; and to this I have now to beg your attention.

A crystal, like every other solid, possesses length, breadth, and thickness ; and the measures of these are three imaginary lines which pass through the centre of the crystal, and are termed the *axes.* They may be denominated *crystallographical* or *geometrical axes,* to distinguish them from the optic axes with which they do not always coincide. Rose defines them to be "certain lines which pass through the centre of the crystal, and around which the faces are symmetrically disposed."

In some forms all these axes are equal in length, as in the cube; and in such cases it is said, that the *axes are similar* or *alike.* Such crystals are termed *equiaxed.* But in a very large proportion of cases the axes are not all equal, and these crystals are said to be *unequiaxed.* Now it is a remarkable circumstance, that the equiaxed crystals are *single* refractors, while the unequiaxed are *double* refractors. This is the first fact demonstrative of the connexion between the forms and the optical properties of crystals.

Of the unequiaxed crystals some have two, others three kinds of axes. If, for example, the length and the breadth of a crystal be alike, but the thickness different, the axes are of two kinds. Such crystals are usually said to have *two dissimilar axes*, but I shall term them *di-unequiaxed*. Other unequiaxed crystals have all their axes unequal; in other words, their length, their breadth, and their thickness are all unequal. Such crystals are generally said to have *three dissimilar axes*, but I shall call them *tri-unequiaxed*. Now, it is most remarkable that the di-unequiaxed crystals are double refractors, with *one* axis of [no] double refraction, while the tri-unequiaxed are double refractors with *two* axes of [no] double refraction. Here is another curious fact, illustrative of the relation which exists between the shape and optical properties of crystals.

Modern crystallographers arrange crystals in six groups, called *systems*. The equiaxed crystals constitute one system, called the *cubic*, *octohedral* or *tessular system*. The di-unequiaxed crystals comprehend two systems; one termed the *square prismatic* or *pyramidal system*, the other called the *rhombohedric* or *rhombohedral system*. The tri-unequiaxed crystals include three systems: one denominated the *right rhombic* or *rectangular prismatic system*; a second termed the *oblique rhombic* or *rectangular prismatic system;* and a third, called the *doubly oblique prismatic system*. The following table will, perhaps, render these statements more intelligible:

GEOMETRICAL CLASSIFICATION OF CRYSTALS.

		Systems.
CLASS 1. Equiaxed crystals (*single refractors*)	…… ……………………	1. Cubic or Octohedral.
CLASS 2. Unequiaxedcrystals (*double refractors*)	*Order* 1. Di-unequiaxed (*one axis of* [*no*] *double refraction*) ….	2. Square Prismatic. 3. Rhombohedric.
	Order 2. Tri-unequiaxed(*two axes of* [*no*] *double refraction*) ….	4. Right Rhombic Prismatic. 5. Oblique Rhombic Prismatic. 6. Doubly Oblique Prismatic.

I shall not at present enter into any further details respecting the geometrical peculiarities of each of these systems, as the subject will be more appropriately considered presently.

3. *Expansibility.*—Between the particles of matter there exist two classes of forces, the one attractive, the other repulsive. By the first, particles are approximated and united to form masses; by the second, they are separated to greater or less distances. Hence attraction and repulsion are antagonizing forces.

Caloric or heat is a repulsive force. It augments the distance between particles and thereby weakens their attractive force; for molecular attraction rapidly diminishes as the distance between the particles increases. Hence solids and fluids, when heated, expand or dilate:

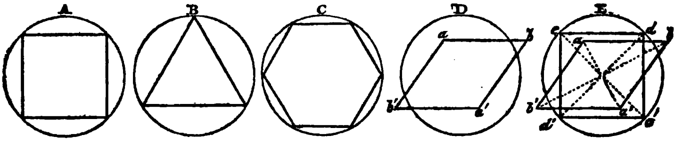
But the force of attraction which exists between the particles of different bodies (solids and liquids) varies considerably: in some being much greater than in others. Hence, the same amount of heat gives rise to a very different degree of expansion in different bodies. In other words, each solid or liquid has an expansion peculiar to itself, owing to the greater or less attractive force which exists between the molecules.

Some crystals, when heated, expand *equally* in all directions, and such I shall accordingly denominate *equiexpanding*. Now it is obvious that in these the existence of equally attractive forces in all directions must be inferred; and it is a curious and striking confirmation of this inference that crystals, which suffer equal expansion in all directions, are singly refracting and equiaxed.

A very large number of crystals, however, dilate, when heated, *unequally* in different directions; and such may be conveniently denominated *unequiexpanding*. In them expansion in one direction is accompanied in some, if not in all cases, with contraction in another direction; and it is, therefore, obvious, that the force of attraction between their particles must be unequal in different directions, the attractive or cohesive force being least in that direction in which the expansion is the greatest. Crystals of this class are doubly refracting and unequiaxed.

The essential difference in shape between an equiexpanding and an unequiexpanding crystal is, that the first can be inscribed within a sphere, the second cannot. We may rudely illustrate this in the lecture-room, by diagram, substituting planes for solids, by inscribing a square, or an equilateral triangle in a circle (fig. 23, A and B). The first will represent the face of a cube, the second that of the regular tetrahedon. Now, it will be perceived that the circumference of the circle passes through all the angular points of the figure about which it is described. All these forms are equiexpanding.

FIG. 23.

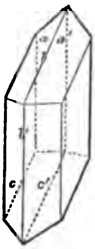


The regular six-sided prism expands unequally in some directions, but equally in others. If now we describe a circle around the terminal faces, it will be perceived that it passes through all the angular points of this face (fig. 23, C), and in all directions, in this plane, the crystal expands equally. The rhombohedron cannot be inscribed within the sphere, because its axes are unequal. If, for example, we attempt to describe a circle around the rhombic face of Iceland spar (fig. 23, D), it will be found that while the obtuse angles ($a\ a'$) are contained within the circle, the acute ones ($b\ b'$) project beyond it. Now, under the influence of heat, this face expands in the direction of the shortest axis, but contracts in that of the longest axis, by which the rhomb approaches to the square, the obtuse angles becoming more acute, the acute ones more obtuse (fig. 23, E).

These illustrations will serve to give some general notions of the relations which exist between the forms and expansibilities of crystals.

The *di-unequiaxed* crystals — that is, the doubly-refracting crystals, which have only one axis of [no] double refraction— expand equally in the direction of the equal crystallographical axes, but differently in that of the remaining one; and we may, therefore, denominate them *di-unequiexpanding crystals.* If, for example, a rhombohedron of Iceland spar be subjected to heat, it expands in the direction of its shortest axis, but contracts in all directions perpendicular to this, and in an intermediate direction it neither dilates nor contracts. Thus, according to Mitscherlich and Dulong, when heated from 32° to 212° Fahr, it actually expands, in the direction of the shorter axis, 0.00286, and contracts in a direction perpendicular to this 0.00056; so that its apparent or relative expansion in this axis is 0.00342 (that is $0.00286 + 0.00056$). Now a necessary consequence of this unequal expansion is an alteration in the angles of the crystal: the obtuse ones become more acute, the acute ones more obtuse. In other words, the rhombohedron approximates to the cube; and in proportion to this change of form is the diminution of doubly refracting energy. Mitscherlich had conjectured that the latter effect would take place, and Rudberg has verified the conjecture. The last mentioned philosopher found, that while the ordinary refraction of Iceland spar underwent little or no change, the extraordinary refraction was considerably diminished by an augmentation of temperature.

Fig. 24.



Crystal of Selenite.

The *tri-unequiaxed* crystals expand when heated, unequally in the direction of all their axes, and, therefore, they may be denominated *tri-unequiexpanding crystals.* When the temperature of selenite is augmented, the inclinations of all its faces suffer changes. Thus according to Mitscherlich by heating it from 32° to 212°, the inclination of the faces $c c'$ was altered 10′50″, that of the faces $a\ a'$ 8′25″, and that of the edges $b\ b'$ only 7′26″.

I have already explained what is meant by the terms *positive* or *attractive*, and *repulsive* or *negative* axes. They refer to optical differences in crystals, for which we find no corresponding geometric or crystallographical differences. Now there have been observed, in the effects of heat on crystals, differences analogous to the optical ones just referred to. Thus, in crystals with a repulsive or negative axis, as Iceland spar, expansion is greatest in the direction of the shortest axis, showing that the molecular attraction in this direction is the weakest; whereas in positive or attractive crystals, as selenite, heat produces less dilatation in a direction parallel to the axis than in a direction perpendicular to it.

"The inclination of the optic axes, in biaxial crystals," says Mr. Lloyd, "is a simple function of the elasticities of the vibrating medium in the direction of three rectangular axes, and the plane of the optic axes is that of the greatest and least elasticities. If, then, these three principal elasticities be altered by heat in different proportions, the inclination of the axes will likewise vary; and if, in the course of this change, the difference between the greatest elasticity and the mean, or between the mean and the least, should vanish and afterwards change sign, the two axes will collapse into one, and finally open out in a plane perpendicular to their former plane. All these variations have been actually observed. Professor Mitscherlich found, that in sulphate of lime the angle between the axes (which is about 60° at the ordinary temperature) diminishes on the application of heat; that, as the temperature increases, these axes approach until they unite; and that, on a still further augmentation of heat, they again separate, and open out in a perpendicular plane. The primitive form of the crystal undergoes a corresponding change, the dilatation being greater in one direction than in another at right angles to it. Sir David Brewster has observed an analogous and even yet more remarkable property in glauberite. At the freezing temperature, this crystal has two axes for all the rays of the spectrum, the inclination of the axes being greatest in red light and least in violet. As the temperature rises, the two axes approach, and those of different colours unite *in succession*; and at the ordinary temperature of the atmosphere, the crystal possesses the singular property of being *uniaxial* for violet light, and *biaxial* for red. When the heat is further increased, the axes which have united open out in order, and in a plane at right angles to that in which they formerly lay, and at a temperature much below that of boiling water, the planes of the axes for all colours are perpendicular to their first position.[*] The inclination of the optic axes in topaz, on the other hand, *augments* with the increase of temperature, and the variation M. Marx has observed, is much greater in the coloured than in the colourless varieties of this mineral[†]."

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[*] *Edin. Trans.*, vol. xi.; and *Phil. Mag.*, 3d series, vol. i., 417.

[†] *Jahrb. der Chemie*, vol. ix.

In conclusion, then, crystals considered with reference to the effects of heat on them, may be thus arranged :—

THERMOTIC CLASSIFICATION OF CRYSTALS.

Class	Order
CLASS 1. Equiexpanding crystals (*single refractors, equiaxed*).	
CLASS 2. Unequiexpanding crystals (*double refractors, unequiaxed*)	*Order* 1. Di-unequiexpanding (*one optic axis, di-unequiaxed*). *Order* 2. Tri-unequiexpanding (*two optic axes, tri-unequiaxed*).

4. *Atoms or Molecules.*—It has been correctly stated by Dr. Brewster,[*] that the polarizing or doubly refracting structure of crystals must "depend on the form of their integrant molecules, and the variation in their density." A few observations on the atoms or molecules of crystals, will not, therefore, be out of place on the present occasion.

Like all other aggregates, crystals are made up of certain small parts conventionally called *atoms* or *molecules*. It is unnecessary to discuss the question of their finite or infinite divisibility; and to obviate the necessity of this, I shall assume with Dumas,[†] that an atom is the smallest particle of a body, which by mere juxtaposition with the particles of other bodies, gives rise to a combination. Hence, therefore, the small parts of any one body which combine chemically with certain small parts of another body, without suffering further division, are what we understand by the terms *atoms* or *molecules*.

As these small parts or atoms are invisible, even when we aid the eye by the most powerful microscope, it is obvious that all observations on their size and shape must be speculative. Two opinions, however, have prevailed with respect to their form, Haüy and others have adopted the notion of their *angular* shape, while Hooke, Wollaston, and other more recent writers, assume them to be *rounded*. If we were to deduce the form of the molecules from that of their aggregates, we should adopt the angular hypothesis; for the most minute fragment of a crystal which we can procure and see, is angular. On the other hand, the spheroidal form of the planetary bodies, the tendency which liquids manifest to assume the spherical shape, and the mechanical facilities which the hypothesis of rounded atoms offers in the grouping of the atoms, have led later writers to adopt almost exclusively the views of Hooke and Wollaston.

But it may be asked, Is the shape of an atom constant? or can it suffer change? May not the atoms of liquids be spherical or ellipsoidal and those of crystals angular? Ellipsoidal forms become angular by mutual compression; and hence may not the ellipsoidal atoms of a liquid become angular in the act of crystallization? The idea has not, to my knowledge, occurred to crystallographers, but it appears to me that the subject well deserves consideration.

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[*] *Phil. Trans.* for 1818, p. 264.

[†] *Traité de Chimie*, t. 1, p. 33, 1828.

A spheroid is said to be *oblate*, when, as in the case of the earth, the shortest diameter is its axis of revolution, but it is *prolate* or *oblong*, when the longer diameter is its axis of revolution. Now the shorter diameter may be regarded as the direction of the greatest attraction, or of compression, while the longer diameter is the direction of least attraction or of dilatation. In the case of the earth it is well known that gravity is greater at the poles than at the equator, a body weighing about $\frac{1}{194}$th more at the former than at the latter. It might, therefore, be supposed that crystals with one positive or attractive axis of double refraction would be formed of oblate spheroids, while those with one negative or repulsive axis, would be made up of prolate spheroids.

But an objection exists to this hypothesis. According to it, *obtuse* rhombohedra ought to have one *positive* axis, while *acute* rhombohedra should have one *negative* axis of double refraction. Now the crystalline form of Iceland spar is an obtuse rhombohedron, but the optic axis of this substance is negative, so that its crystalline form is that which is produced by an oblate spheroid, while its optical property is that of a prolate spheroid. To obviate this objection, Dr. Brewster* suggests that the molecules have the form of oblate spheroids, whose polar is to their equatorial axis as 1 to 2.8204, and that they were originally more oblate, but have been rendered less so by the force of aggregation, which dilated them in the direction of the smaller axis.

In point of fact, however, this assumption does not entirely obviate the difficulty, as the spheroids are still supposed to be oblate, though their axis is a negative one; and it appears probable, that the same force which would render the axis negative, should change the shape of the spheroid from the oblate to the prolate. Moreover, Dr. Brewster's explanation involves the improbable supposition that the original very oblate spheroids if "placed together without any forces which would alter their form," would "compose a rhombohedron with a greater angle, and having no double refraction."

On the assumption that the axes of the atoms of crystals bear the same relations to each other that the axes of the systems of crystals themselves do, I have drawn up the following table of the supposed shapes of the atoms:

TABLE OF THE SHAPES OF THE ATOMS OF CRYSTALS.

			Systems of Crystals.
Ellipsoids.	Class 1. Equiaxed (*spheres*)		1. Cubic
	Class 2. Unequiaxed	*Order* 1. Two equal axes (*spheroids*)	2. Rhombohedric 3. Square Prismatic
		Order 2. Three unequal axes	4. Right Prismatic 5. Oblique Prismatic 6. Doubly Oblique

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* *Phil. Trans.*, 1830.

The doubly refracting structure is not inherent in the molecules themselves. Quartz or crystallized silica doubly refracts; but tabasheer, opal, and melted quartz, all siliceous substances, do not. Ice doubly refracts, while water singly refracts. What is the reason of this?

It will be generally admitted, I presume, that the double refraction of ice is a molecular property, and is associated with the shape of the atom; and hence, if the atoms of water have the same form as those of ice, they ought also to possess the doubly refracting property of the latter. Now, the advocates for the hypothesis of the unchangeability of atomic forms contend, that in ice the atoms are symmetrically and regularly arranged, with their axes pointing in the same direction; while in water they are unsymmetrically or irregularly arranged or jumbled together in such a manner that their axes have every possible direction, so as to create a general equilibrium of the polarizing forces. But, if this were the case, two specimens of water would scarcely ever present the same optical properties. If, by any accident, the axes of a large majority of the molecules should happen to be arranged in the same direction, the liquid would then possess a doubly refracting property. Now, it appears to me, that no hypothesis can be correct which ascribes to accident or chance a constant and invariable property of a body; for I hold, that, except when approaching the freezing point, liquid water is invariably a single refractor.

But on the assumption that the shapes of atoms are, to a certain extent, capable of change, the difficulty is easily obviated. Suppose the atoms of liquid water to be spheres, and that in the act of freezing they become spheroids, the expansion of water in the act of freezing, the doubly refracting property, and the crystalline form of ice would then be readily explicable.

A consistent explanation of Dimorphism can scarcely be offered except on the assumption of the changeability of the shapes of the atoms. Carbonate of lime, for example, crystallizes in two distinct and incompatible forms, the one belonging to the rhombohedric, the other to the right prismatic system. In the first case, we call it Iceland-spar; in the other, arragonite. Iceland-spar has one negative optic axis, arragonite has two negative optic axes. The shapes of the atoms of these bodies must, therefore, be different. Admit that, under certain circumstances, the atom of carbonate of lime can change its shape, and all difficulty as to the production of these forms is at an end.

We suppose, therefore, that "when in the process of evaporation or cooling, any two molecules are brought together by the forces or polarities which produce a crystalline arrangement, and strongly adhere, they will mutually compress one another." If the compression in three rectangular directions be equal, the crystal will be a singly refracting one: if the compression in two directions be equal but different in the third, the crystal will be a doubly refracting one with one optic axis: and, lastly, if the compression be different in each of the three directions, the crystal will doubly refract, and have two optic axes.

5. *Molecular Forces.*—Between the molecules of crystals, as well as of other bodies, there exist attractive and repulsive forces, in virtue of which the molecules are retained, not in contact, but within certain distances of each other. These forces are antagonists, and, therefore, the molecules acting under their influence, take up a position of equilibrium, where the two opposing powers counterbalance each other.

But in crystals it is necessary to admit, besides ordinary *attraction* and *repulsion*, a third molecular force called *polarity*, which may be regarded either as an original or a derivative property. Without this it is impossible to account for the regularity of crystalline forms. Under the influence of a mutually attractive force particles would adhere together and form masses; the shapes of which, however, would be subject to the greatest variety; and though occasionally they might happen to be regular, yet this could not constantly be the case.

The simplest conception we can form of polarity is that it depends on the unequal action of molecular attraction or repulsion in different directions. A molecule endowed with unequal attractive forces in different directions may be said to be possessed of polarity.

A crystal has length, breadth, and depth or thickness. It is composed of molecules accumulated in three different directions corresponding to these three measurements; and it is obvious, therefore, that to account for their cohesion we must suppose that they attract each other in three directions; moreover, as the relative intensity of their attraction in these directions is, in many cases, unequal, it might be even supposed that they are three different kinds of attractions. To render this subject intelligible I shall make use of some illustrations employed by Dr. Prout in one of the Bridgewater Treatises.

FIG. 24.

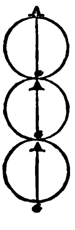


FIG. 25.

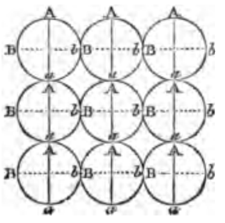
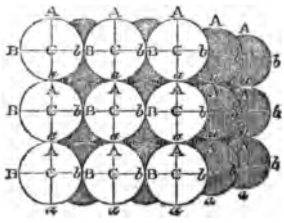


FIG. 26.



Suppose three molecules to adhere together to form a single *row*, line, or string of molecules, in virtue of an attractive force which I shall distinguish by the name of the *length force*. The points *A A A* or *a a a* are supposed to mutually repel each other, while *Aa Aa Aa* mutually attract (fig. 24).

Let us further suppose that three such rows of particles cohere in virtue of an attractive force acting in a direction perpendicular to the first. We may distinguish this as the *breadth force*. The points *B B B* or *b b b* are supposed to mutually repel, while *Bb Bb Bb* mutually attract. These three rows of particles by their cohesion form a *plane* (fig. 25).

Again let us assume, that three such planes cohere together, in virtue of an attractive force acting in a direction perpendicular to both the other forces. This force we may denominate the *depth force*. The points *C C C* or *c c c* are assumed mutually to repel, while *Cc Cc Cc* mutually attract. These three planes by their union form a *solid* (fig. 26).

Thus, then, we suppose that the molecules of crystals have three rectangular axes of attraction, or " lines along which they are most powerfully attracted, and in the direction of which they cohere with different degrees of force."

Though for convenience and facility of explanation I have employed the terms length-force, breadth-force, and depth-force, I by no means wish you to suppose that I adopt the notion of the distinct nature of these forces. They may be, perhaps they are, one force acting in three directions.

These forces may be *equal* or *unequal*, and in the latter case two only, or all three, may be unequal. That is, in some crystals the length-force may be equal to the breadth-force, and this to the depth-force. Or two only of the forces may be equal, the third being unequal: or, lastly, all three may be unequal.

As I have already had frequent occasion to speak of the *elasticity* of crystals, and as I shall again have to refer to it, I think it proper to explain what is meant by it. I have stated that the molecules of bodies are not in actual contact, but are separated by greater or less intervals. They are kept from actual contact to which attraction urges them, by repulsion, while their further separation is opposed by attraction.

Now we may disturb their state of equilibrium. We may, for example, by some compressing force, compel the particles to approach nearer to each other; but when the disturbing cause ceases to act, the particles after a few oscillations take up their original position. This then is what we mean by elasticity, which is obviously a consequence of attraction and repulsion. An elastic body is one which has the property of restoring itself to its former figure after any force which has disturbed it is withdrawn.

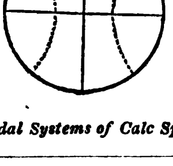
If by any force we approximate the particles of an elastic body, we augment its elasticity, and *vice versâ*. Now, as it is repulsion which opposes the approximation of particles, it appears that it is this force principally which confers on bodies the property called elasticity.

In some crystals their elasticity is equal in three rectangular directions. Such crystals may be denominated *equielastic.* Others, however, have unequal elasticities in different directions, and may be termed *unequielastic.* The first are single refractors, the latter are double refractors. Of the unequielastic crystals, some have two of their three elasticities equal, others have all three of their elasticities unequal: the first may be termed *di-unequielastic*—the second, *tri-unequielastic.*

The elasticity in the crystallographical axis may fall short of or exceed that in other directions: in the first case, crystals are said to have a negative or repulsive axis, or an axis of dilatation; in the latter case, they are said to have a positive or attractive axis, or an axis of compression.

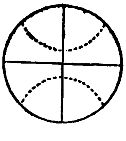
By experiments made by Savart*, on the mode of sonorous vibration of crystalline substances, it has been shown, that the negative or repulsive axis is the axis of least elasticity, while the positive or attractive axis is the axis of greatest elasticity. "In carbonate of lime," he observes, "it is the small diagonal of the rhombohedron which is the axis of least elasticity, whilst it is that of greatest elasticity in quartz." To be convinced of the accuracy of this assertion, it is sufficient to cut, in a rhombohedron of carbonate of lime, a plate taken parallel to one of its natural faces, and to examine the arrangement of its two nodal systems, one of which consists of two lines crossed rectangularly, which are always placed on the diagonals of the lozenge, the primitive outline of the plate; and the other is formed of two hyperbolic branches, to which the preceding lines serve as axes, (fig. 27), but with this peculiarity, that it is the small diagonal

FIG. 27.



Nodal Systems of Calc Spar.

FIG. 28.



Ditto of Quartz.

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* Taylor's *Scientific Memoirs,* vol. 1.

which becomes the first axis of the hyperbola, whilst it is *its* second axis in the corresponding plate of rock crystal (fig. 28).

The following table shows the relation between the elasticities and shapes of crystals:

TABLE OF THE ELASTICITIES OF CRYSTALS.

		Systems.		
Class 1. Equielastic crystals		1. Cubic.		
Class 2. Unequielastic crystals	*Order* 1. Di-unequielastic	2. Rhombohedric 3. Square Prismatic	Elasticity in crystallographical axis, either	*a.* Minus (negative or repulsive) or *b.* Plus (positive or attractive)
	Order 2. Tri-unequielastic	4. Right Prismatic 5. Oblique Prismatic 6. Doubly Oblique Prismatic		

Conclusions.—From the preceding remarks it will appear,

1. That *singly refracting crystals* are equiaxed, equiexpanding, equielastic, and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of spherical atoms.

2. That *doubly refracting crystals* are unequiaxed, unequiexpanding, unequielastic, and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of either spheroidal atoms or ellipsoids with three unequal axes.

3. That *uniaxial crystals* are di-unequiaxed, di-unequiexpanding, di-unequielastic, and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of spheroidal atoms.

4. That *biaxial crystals* are tri-unequiaxed, tri-unequiexpanding, tri-unequielastic; and, on the ellipsoidal hypothesis of molecules, may be assumed to be made up of ellipsoids having three unequal axes.

5. That doubly refracting crystals, having a *negative* or *repulsive axis*, expand more, and have less elasticity in the direction of the axis than in directions perpendicular to this.

6. Lastly, that doubly refracting crystals, having a *positive* or *attractive* axis, expand less, and have more elasticity in the direction of the axis than in directions perpendicular to this.

I shall now go through the six systems of crystals, separately pointing out the most important of their optical and other properties.

SYSTEM I.

THE CUBIC OR OCTOHEDRAL SYSTEM.

Synonymes.—The *regular*, the *tessular*, the *tesseral*, or the *isometric system.*

Forms.—The forms of this system are either *homohedral* or whole forms, or *hemihedral* or half forms.

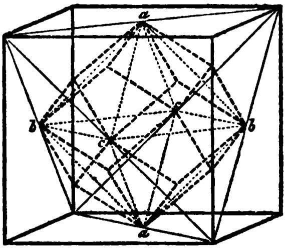
Homohedral Forms.

1. Regular Octohedron.
2. Cube or Hexahedron.
3. Rhombic Dodecahedron.
4. Icositetrahedron.
5. Triakisoctohedron.
6. Tetrakishexahedron.
7. Hexakisoctohedron.

Hemihedral Forms.

1. Tetrahedron or Hemioctohedron.
2. Hemicositetrahedron or Pyramidal Tetrahedron.
3. Hemitriakisoctohedron.
4. Hemihexakisoctohedron.
5. Hemitetrakishexahedron or Pentagonal Dodecahedron.
6. Hemioctakishexahedron.

FIG. 29.



Four forms of the Cubic System ; viz., Cube, Regular Tetrahedron, Rhombic Dodecahedron, and Regular Octohedron.
a a, b b, c c. The three rectangular equal axes.

Crystals.—Of the fifty-five or fifty-six simple or elementary bodies which have been hitherto discovered, the crystalline forms of not more than eighteen have been ascertained. Of this number, no less than thirteen are referable to the cubic system, namely *bismuth, copper, silver, gold, platinum, iridium* (?), *iron, lead, titanium, mercury, sodium, phosphorus* and *diamond.* Now it appears *à priori* probable that simple bodies would have spherical atoms, and, therefore, the fact that the above named substances crystallize in forms belonging to the cubic system, has been adduced as an additional evidence of their simple nature.

A considerable number of binary compounds also belong to this system — as the *chlorides of sodium, potassium,* and *silver; sal ammoniac ;* the *bromide* and *iodide of potassium ; fluor-spar,* and the *sulphurets of zinc* (blende), *lead* (galena), *silver,* and *iron* (pyrites).

Some substances, which contain more than two elements, also belong to this system, as *alum* and *garnet.*

Now, if the cubical form be an argument for the simple nature of the metals, why, it may be asked, do so many compound bodies present the same form ? To this we can offer no satisfactory reply ; and I think, therefore, we may conclude with Dr. Wollaston, "that any attempts to trace a general correspondence between the crystallographical and supposed chemical elements of nature, must, in the present state of the sciences, be premature."

Properties.—The crystals of this system have the following properties: they are equiaxed singly refracting, equiexpanding and equielastic. We assume their molecules to be spherical.

When examined in the polariscope they present no traces of colour.

Exceptions.—A few exceptions exist to some of the preceding statements; but they are probably more apparent than real.

1. Several crystals of this system, as the diamond, fluor-spar, alum, and common salt, sometimes exhibit traces of a doubly refracting structure. But this is ascribable to irregularities of crystallization, or to the operation of compressing or dilating forces.

2. *Boracite* (a compound of boracic acid and magnesia) crystallizes in the general form of the cube; the edges of which are replaced, and the diagonally opposed solid angles dissimilarly modified. Instead, however, of being merely a single refractor, as its shape would lead us to expect, Dr. Brewster found that it was a double refractor, with one positive axis of double refraction in the direction of a line joining two opposite solid angles of the cube. So that, in point of fact, it possesses the properties of a rhombohedric crystal. We may, therefore, regard it as a rhombohedron, whose angles differ from a right angle by an infinitely small quantity.

3. *Analcime* or *cubizite* (hydrated silicate of alumina and soda) constitutes another remarkable exception to the general rule, that crystals of the cubic system are devoid of a doubly refracting structure. The most usual form of this crystal is the icositetrahedron. Now if we suppose, says Dr. Brewster, its contained cube "to be dissected by planes passing through all the twelve diagonals of its six faces, each of these planes will be found to be a plane of no double refraction or polarization." All intermediate portions doubly refract. From every other known doubly refracting crystal, analcime differs in the circumstance, that all its particles do not equally possess the property of double refraction, those in the planes above mentioned being devoid of this power, and the others possessing it in proportion to the squares of their distances from these planes. It differs from unannealed glass in the fact that a change in its external form does not give rise to a change in its polarizing power; but each fragment possesses the same optical property, when it is detached from the mass, that it had when naturally connected with its adjacent parts. Analcime, therefore, is a complete optical anomaly.

It has been suggested, that these curious optical properties may depend on the presence of both a doubly and a singly refracting mineral; and the fact, that the large opake crystals of analcime, found in the valley of Fassa in the Tyrol, are traversed by plates of apophyllite (a doubly refracting crystal), lends support to this hypothesis.

SYSTEM II.

THE SQUARE PRISMATIC SYSTEM.

Synonymes.—The *four-membered* or *two- and one-axed*, the *pyramidal*, the *tetragonal*, or the *monodimetric system*.

Forms.—The forms of this system are either *homohedral* or whole forms, or *hemihedral* or half forms.

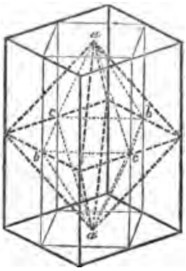
Homohedral Forms.

1. Octohedron with square base.
2. Terminal Face or Horizontal Plane.
3. Square Prism (of two positions).
4. Dioctohedron or Eight-sided Pyramid.
5. Eight-sided prism.

Hemihedral Forms.

1. Hemioctohedron or Tetrahedron.
2. Hemi-dioctohedron.

FIG. 30.



Four forms of the Square Prismatic System; viz., Two Square Prisms in different positions, and Two Octohedra with square bases.
a a. Principal axis. *b b*, *c c*. Secondary axes.

Crystals.—Among the crystals [*] of this system are *chloride of mercury* (calomel), *bicyanide of mercury*, *ferrocyanide of potassium* (yellow prussiate of potash), *peroxide of tin*, *copper pyrites*, *zircon*, and *apophyllite*.

Properties.—The crystals of this system have the following properties: They are di-unequiaxed, doubly refracting with one optic axis, di-unequiexpanding, and di-unequielastic. We assume their molecules to be either prolate or oblate spheroids.

The two equal rectangular geometric axes of this system are called *secondary axes*; while the third or odd one, which may be greater or less than the others, is the *principal* or *prismatic axis*, or the *crystallographical axis*, or the *axis of symmetry*. The optical characters of this system are the following: The crystals are doubly refracting, with one optic axis which coincides with the principal axis.

If a thin slice of a crystal of this system, cut perpendicularly to the principal axis, be placed in the polariscope, it presents a system of circular rings, with a cross, which is either black or white, according to the relative positions of the polarizer and analyzer.

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[*] Sowerby (*Ann. Phil.* xvi. 223.) mentions crystals of *Palladium* in the form of octohedra with a square base and of symmetrical prisms.

Ferrocyanide of potassium (commonly called *prussiate of potash*) may be conveniently used to show these effects. As found in commerce it usually occurs in the form of truncated octohedrons having a square base. It should be split with a lancet in the direction of its laminæ, that is, perpendicularly to its principal axis. Plates, of about a quarter of an inch or more in thickness, serve for the polariscope. They present a cross, and a negative system of circular rings; but the yellow colour of the crystal affects the brilliancy of the tints.

Zircon (a compound of silica and zirconia) is valuable for optical purposes, on account of its being a *positive* uniaxial crystal. Hence if a plate of it, which gives a system of rings of the very same size as that produced by a plate of Iceland spar (a *negative* uniaxial crystal) be superposed over the latter plate, the one system of rings is completely obliterated by the other; and the combined system exhibits neither double refraction nor polarization.

I shall defer all explanation respecting the rings and cross of this system, until I speak of Iceland spar (a crystal of the rhombohedric system).

Exceptions.—Some exceptions to the above mentioned properties of the crystals of this system exist, and require to be noticed.

1. *Ferrocyanide of potassium* is subject to irregularities of crystallization; and certain specimens present a double system of rings, or, in other words, are biaxial. Certain uniaxial specimens give a positive system of rings.

2. *Apophyllite* or *Fisheye-stone* (a compound of silica, lime, potash, and water) possesses some remarkable properties. In the most common variety, that from Cipit in the Tyrol, the diameters of the rings are nearly alike for all colours — those of the green rings being a little less. Some specimens of apophyllite, called by Dr. Brewster *tesselated apophyllite*, present, in the polariscope, a tesselated or composite structure, instead of the ordinary cross and circular rings. They will be described hereafter among the tesselated or intersected crystals.

SYSTEM III.

THE RHOMBOHEDRIC SYSTEM.

Synonymes.—The *three- and one-axed*, the *klinohedric*, the *hexagonal*, or the *trimetric system.*

Forms.—The forms of this system are either *homohedral* or *hemihedral.*

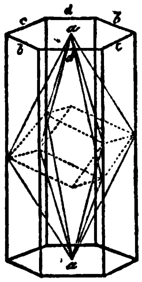
Homohedral Forms.

1. Double Six-sided Pyramid (Hexagondodecahedron).
2. Right Terminal Face (Horizontal Plane).
3. Hexagonal Prism.
4. Double Twelve-sided Pyramid (Didodecahedron).
5. Twelve-sided Prism.

Hemihedral Forms.

1. Rhombohedron (Hemidodecahedron).
2. Scalenohedron.

FIG. 31.



Three forms of the Rhombohedric System; viz., the Hexagonal Prism, the Scalene Dodecahedron and the Rhombohedron.
a a. The principal axis. *b b, c c, d d.* The secondary axes.

Crystals.—To this system belong some bodies supposed to be simple or elementary; viz., *antimony*, *arsenicum*, and *tellurium.*[*]

Plumbago or *graphite* and the *native alloy of iridium* and *osmium* also belong to this system.

Ice, magnetic iron pyrites, cinnabar, chloride of calcium, Iceland spar, carbonates of iron and zinc, dolomite (magnesian carbonate of lime), *nitrate of soda, hydrate of magnesia, tourmaline, talc, beryl, chabasite, quartz,* and *one-axed mica* belong to this system. And here it may be necessary to remark, that the substance known to mineralogists by the name of *mica*, and which, in trade, is usually but improperly termed *talc*[†], varies in its crystalline forms and optical properties. One kind crystallizes in regular hexagonal prisms, which cleave with extreme facility in one direction, viz., perpendicularly to their axis. This has only one axis of [no] double refraction, and consequently when a lamina of it is placed in the polariscope it presents only one system of circular rings traversed by a cross. This is the kind called *rhombohedral* or *uniaxial mica*, the majority of specimens of which have a negative or repulsive axis, though some have a positive or attractive one. But there is another kind of mica, of more frequent occurrence in the shops, and which is called by mineralogists *prismatic* or *diaxial mica.* It has two axes of double refraction, and consequently when a plate of it is placed in the polariscope, two systems of coloured rings are perceived. This kind of mica exists in two forms; one is crystallized in right prisms, the other in oblique prisms. Hence I shall distinguish the one as *right prismatic mica*, the other as *oblique prismatic mica*. They will be described hereafter. In conclusion, then, the kinds of mica may be thus arranged:

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[*] Rose inserts "*Palladium* (?)" among rhombohedric crystals.

[†] Talc is readily distinguished from mica by its greasy or unctuous feel. The most familiar kind of talc is that sold in the shops under the name of *French chalk.* It is talc in an indurated earthy form.

- Mica .....
  - Rhombohedric or Uniaxial
    - With a negative axis, or
    - With a positive axis.
  - Prismatic or Diaxial ......
    - Right Prismatic.
    - Oblique Prismatic.

The principal constituents of mica are silica and alumina. But it also contains potash and sesquioxide of iron.

Properties.—The forms of this system possess four axes†; viz., three equal ones, called the *secondary axes*, placed in one plane, and crossing in the centre at an angle of 60°; and a fourth, termed the *principal axis*, or the *axis of symmetry*, or the *crystallographical axis*, perpendicular to the others, from which it differs in length. They are double refractors, with one optic axis coincident with the principal axis. They are di-unequiexpanding bodies, the expansion being different (greater or less) in the principal axis from that in the secondary ones. They are di-unequielastic; the elasticity in the principal axis being either more or less than that in the secondary axes. With regard to the atoms, we may assume their shape to be spheroids.

Iceland spar (Ca O. CO_2) may be conveniently used to illustrate the optical properties of the crystals of this system. It occurs in rhomboidal masses, which by cleavage yield obtuse rhombohedra. The line which joins the two obtuse summits of one of these rhombohedra, is called the *shortest* or *principal axis*, the *crystallographical axis*, the *axis of the rhomboid*, or simply the *axis*. A plane drawn through this axis, perpendicularly to a face of the crystal, is called the *principal section*. This section belongs rather to a face than to the entire crystal, for each face has its own. Now when the incident rays are perpendicular to the face of the crystal, both the ordinary and extraordinary rays are always found in the same plane, so that the deviation of the extraordinary pencil takes place in the plane of the principal section. Every plane in the interior of the crystal, which is perpendicular to the axis, is called a *section perpendicular to the axis*, or the *equator of double refraction*. In this plane the doubly refracting force is at a maximum, and when a ray is incident in this plane, the resulting extraordinary and ordinary rays are both in the same plane.

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† The description adopted in the lectures is that of Weiss and Rose; some other writers admit only three axes. Thus, Turner (*Elements of Chemistry* 7th ed., p. 588) describes three equal but not rectangular axes; while Griffin (*System of Crystallography*, pp. 151 and 258) admits three rectangular but unequal axes. Neither of these modes of descriptions appear to me so completely to connect the form with the optical and other properties of the crystals, as Weiss and Rose's method.

If a plate of Iceland spar, cut perpendicularly to the principal or shortest axis, be placed in the polariscope, the polarizing and analyzing plates being crossed, we observe coloured curves or concentric rings intersected by a rectangular black cross, the arms of which meet at the centre of the rings (fig. 32).

FIG. 32.

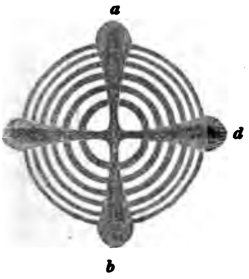


FIG. 33.

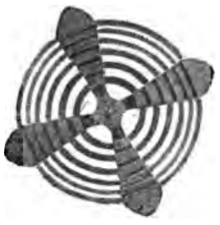
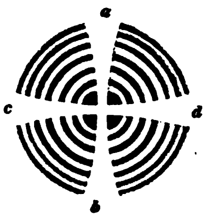


FIG. 34.



The coloured curves or rings are called *the lines of equal tint*, or *isochromatic lines* (from ἴσος *equal* and χρωματικὸς *coloured*). In this and other uniaxial crystals, they are disposed in concentric circles, and are similar to Newton's rings seen by reflection.

If we revolve the plate of Iceland spar on its axis, the rings and cross preserve the same position; but if either the polarizing or analyzing plate be rotated, some remarkable changes occur.

Suppose the analyzing plate to be turned 45° round the incident ray in a left-handed direction, we observe that the original or primary coloured rings grow fainter or more dilute, and the cross seems to shift its position to the left, while its blackness lessens and is replaced by another set of rings, which alternate with, and are complementary to, the original curves (fig. 33).

If the analyzing plate be rotated 45° further in the same direction, that is 90° to the first or original position, the black cross is replaced by a white one, and the original set of coloured rings is succeeded by a second or complementary set, the rings of which are intermediate to the original ones, and are similar to Newton's rings seen by transmission (fig. 34).

If the system of rings with a black cross (fig. 32) were superposed in the system with the white cross (fig. 34) white light would be reproduced.

If the incident polarized light be white, the rings consist of compound tints produced by the superposition on each other of rings formed by each of the homogeneous rays composing white light.

Of course, if the rings of all the colours were of the same size, the resulting system would consist of black and white rings; but being of different dimensions, we obtain a system of different colours. In this case, the cross is either black or white, not coloured.

If the incident polarized light be homogeneous the rings consist of rings of the colour of the light employed separated by black rings. Thus, suppose red light to be used, the rings will be alternately red and black; whereas if blue light be employed, they will be alternately blue and black. Their size varies with the colour of the light: red produces the largest, violet the smallest system of rings. In all cases in which homogeneous light is employed the cross is either a black or a coloured one.

The radii of the bright rings are as the square roots of the odd numbers, 1, 3, 5, 7, &c.; while those of the dark rings are as the square roots of the even numbers, 2, 4, 6, 8, &c. In other words, the squares of the diameters of the bright rings are as the odd numbers, 1, 3, 5, 7, &c.; while the squares of the diameters of the dark rings are as the even numbers, 2, 4, 6, 8, &c.

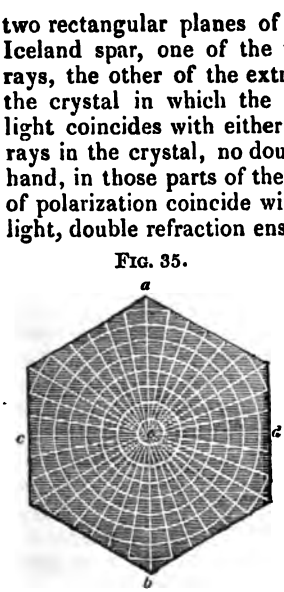
Squares of the diameters of the ...	*Bright* rings	1	—	3	—	5	—	7	—
	Dark rings	—	2	—	4	—	6	—	8

The actual diameter and breadth of the rings are increased by diminishing the thickness of the crystalline plate. To speak more precisely, the radii of the rings are inversely as the square root of the thickness of the plate; and, therefore, the rings are smaller with a thick plate than with a thin one. Thus while a plate of a given thickness will produce a system of rings, the whole of which can be seen at once, a plate considerably thinner will give rings of so much larger diameter and greater breadth, that the whole system cannot be taken in at once by the eye. It is obvious, therefore, that the comparative doubly refracting power of two uniaxial crystals may be ascertained by observing the size of the rings produced by plates of equal thickness: with a powerful doubly refracting crystal the rings are less than with a crystal possessing this property in a weaker degree. In fact, the radii of the rings are inversely as the doubly refracting power of the crystal.

Let us now endeavour to explain generally the origin of the coloured rings and of the cross, according to the undulatory hypothesis; and, for precision and brevity of description, I shall suppose that tourmaline plates are used in the polariscope both for polarizing and analyzing.

The first tourmaline plate polarizes the light which is then incident on the Iceland spar. In their progress through the latter, some of the polarized rays suffer double refraction, others are transmitted without undergoing this change. For there are two rectangular planes of polarization of the luminous rays in Iceland spar, one of the plane of polarization of the ordinary rays, the other of the extraordinary rays; and in those parts of the crystal in which the plane of polarization of the incident light coincides with either of the planes of polarization of the rays in the crystal, no double refraction occurs. On the other hand, in those parts of the crystal in which neither of its planes of polarization coincide with the plane of the incident polarized light, double refraction ensues.

Fig. 35.



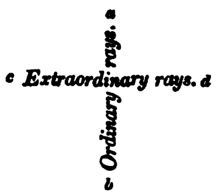
All the ordinary rays which emerge from the crystal, are polarized in planes which pass through the principal axis of the crystal: while the extraordinary rays will be polarized in planes perpendicular to these. Let fig. 35 represent the crystalline plate cut perpendicularly to the axis *e*. The radiating white lines represent the planes of polarization for the ordinary rays, and the circular white lines the planes of polarization for the extraordinary rays.

The two sets of rays (that is, the ordinary and the extraordinary) form two cones of refracted rays, having a common axis coincident with the axis of the crystal. The summit, or apex of each cone, will be at the eye of the observer; and the diameter of the base of the cone will of course vary according to its distance from the eye. The different rays, of which each cone is made up, undergo different changes. Those which form the axis of the cone, traverse the plate at a perpendicular incidence, and, therefore, are not refracted; while those which pass through the plate obliquely, undergo double refraction.

The ordinary or the extraordinary rays forming the same cone have not all an equal intensity at different parts of its circumference. For if the plane of polarization of the incident light be identical with or parallel to *a b*, fig. 35, it is evident, that while the intensity of the ordinary rays will be at a *maximum* in the plane *a b*, and at a *minimum* or *nil* in a direction perpendicular to this *c d*, the intensity of the extraordinary rays will be at a *maximum* in the plane *c d*, and at a *minimum* or *nil* in a direction perpendicular to this, *a b*.

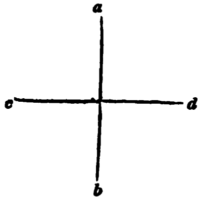
Hence those rays which are incident on the crystal in the plane *a b*, traverse the plate without having their plane of polarization charged, emerge as *ordinary* rays, and, by the subsequent action of the analyzing plate, form two arms of the rectangular cross, *a b* (fig. 36). Those rays which are incident on the crystal at any point of the line *c d* also traverse the crystal without having their plane of

FIG. 36.



polarization changed, but they emerge as *extraordinary* rays, and, by the subsequent action of the analyzer, form the remaining two arms of the rectangular cross *c d* (fig. 36). The two sets of polarized incident rays which thus traverse the crystal, without having their plane of polarization changed, and emerge, the one as the ordinary, the other as the extraordinary rays, form either a black or a white cross, according as they are either suppressed or transmitted by the second or analyzing tourmaline. If the two tourmalines be crossed the rays are suppressed—if they coincide the rays are transmitted. In the first case we perceive a black cross, in the second a white one.

FIG. 37.



Thus, then, all the rays which emerge from the second surface of the crystal, at any point of the two lines *a b*, *c d* (fig. 37), will not be divided into two, nor have their planes of polarization altered. But all the polarized rays which are incident on the crystal in any direction intermediate between the positions *a b* and *c d* suffer double refraction, since their planes of polarization coincides neither with the plane of polarization of the ordinary, nor with that of the extraordinary rays; that is, the vibrations of the incident rays are resolved into two sets, one which forms the ordinary rays, and the other perpendicular to it, which forms the extraordinary rays. The two systems of waves, produced by these two sets of vibrations, proceed through the crystal with unequal velocities and describe different paths; consequently they emerge in different phases, that is, in a condition for suffering interference by the action of the analyzer. In my last lecture, however, I so fully explained the agency of the analyzer in giving rise to the phenomena of colour, that I need not now enter further into it. I shall, therefore, only add, that the coloured rings owe their origin to interference.

A circumstance which affects the formation of the rings, is the inclination of the polarized rays to the optic axis of the crystal. In the axis itself, where the arms of the cross pass athwart each other, no colour is produced, consequently there can be, in this position, no double refraction. But those rays which suffer double refraction and produce colour, traverse the crystal obliquely, and at an inclination to the optic axis, and the obliquity or inclination augments in proportion as we recede from the centre or axis. Now the effect of an increase in the inclination of the rays to the optic axis is equivalent to an increase of thickness in the crystal. Hence it is obvious why we have rings, and not an uniform tint, as in the case of the thin films of selenite described in our last lecture. Moreover, it is obvious that at equal distances around the axis the inclinations will be the same, and consequently the similar tints will be found at equal distances from the axis; in other words, the lines of equal tint or isochromatic lines will be disposed in concentric circles.

That the tints of the system of rings accompanying the black cross should be complementary to those which accompany the white cross, will be readily understood from what was stated in the last lecture respecting the office of the analyzing plate.

The rings of the two systems do not occupy the same position, but are transposed; that is, the bright rings of the one system occupy the position of the dark rings of the other system. The cause of this is obvious—the rings of the two systems are produced by different rays. The two sets of rays which successively pass through the tourmaline analyzing plate in its two positions, would, if this plate were not interposed, pass simultaneously and produce an uniform tint of the same colour as that of the incident light. In other words, without the analyzer neither cross nor rings would be perceived.

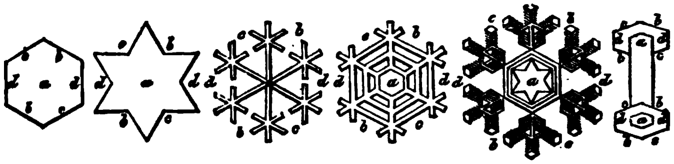
But why, it may be asked, is the maximum brilliancy of the rings at the middle of the four quadrants; that is, in lines or directions which are equidistant from the two nearest arms of the cross? Because it may be replied, it is at these spots that the ordinary and extraordinary rays (produced by double refraction) are equal. On either side of these directions, the ordinary ray has either a greater or less intensity than the extraordinary one.

Iceland spar has, as I have already stated, a negative or repulsive axis; and I shall take this opportunity of explaining the method used by Dr. Brewster for distinguishing whether the axis of a crystal be positive or negative. Take a film of selenite (sulphate of lime), and mark on it the *neutral axes;* then, by a little wax, attach it to a plate of Iceland spar (cut so as to show the rings), and place them in the polariscope. If the film by itself produces the red of the second order, it will now, when combined with the Iceland spar, obliterate part of the red ring of the second order in two alternate and opposite quadrants (either *a c* and *b d*, or *a d* and *b c*, figs. 32 and 34). The line of the film which crosses these two quadrants at right angles to the rings is the *principal axis* of selenite, and should be marked as such. Then if we wish to examine whether any other system of rings is positive or negative, we have only to cross the rings with the principal axis " by interposing the film: and if it obliterates the red ring of the second order in the quadrant which it crosses, the system will be negative; but if it obliterates the same ring in the other two quadrants which it does not cross, then the system will be positive. It is of no consequence what colour the film polarizes, as it will always obliterate the tint of the same nature in the system of rings under examination."

Plates of *tourmaline*, obtained by cutting the crystals at right angles to the principal or prismatic axis, as described in my first lecture (fig. 6, p. 18), present circular rings and a cross when examined by the polariscope.

Ice belongs to the rhombohedric system. The beautiful and regular, though varied, crystalline forms of snow may be regarded as skeleton crystals of this system. I have here depicted (see fig. 38) a few forms taken from Captain Scoresby's work on the Arctic Regions; and in them you may readily trace the three secondary axes (*b b*, *c c*, *d d*), placed in the same plane, and inclined to each other at an angle of 60°, while the fourth or principal axis (*a a*) is perpendicular to the other three.

FIG. 38.



Crystals of Snow.

Now, if you take a sheet of clear ice, about an inch thick, and which has been slowly formed in still weather, and examine it by the polariscope, you will readily detect the circular rings and cross. The system of rings formed by ice is positive or attractive; and, therefore, is of an opposite kind to that of Iceland spar.

Exceptions.—To the general properties of crystals of the rhombohedric system some exceptions exist.

1. In Iceland spar, beryl, and other crystals of this system, the rings are not unfrequently distorted, owing to irregularities of crystalline structure.

2. *Quartz* belongs to this system, but its optical phenomena are very different to those of any other crystal, and will be described in my next Lecture, under the head of *circular polarization.*

3. *Amethyst* is another exception, which I shall hereafter describe.

4. *Chabasite* (a mineral compound of silica, alumina, lime water, and potash) is a rhombohedral crystal, sometimes endowed with remarkable optical properties. "In certain specimens of this mineral," says Dr. Brewster, "the molecules compose a regular central crystal, developing the phenomena of regular double refraction; but in consequence of some change in the state of the solution, the molecules not only begin to form a hemitrope crystal on all the sides of the central nucleus, but each successive stratum has an inferior doubly refracting force

till it wholly disappears. Beyond this limit it appears with an opposite character, and gradually increases till the crystal is complete. In this case the relative intensities of the axes or poles from which the forces of aggregation emanate, have been gradually changed, probably by the introduction of some minute matter, which chemical analysis may be unable to detect. If we suppose these axes to be three, and the foreign particles to be introduced, so as to weaken the force of aggregation of the greater axis, then the doubly refracting force will gradually diminish with the intensity of this axis, till it disappears, when the three axes are reduced to equality. By continuing to diminish the force of the third axis, the doubly refracting force will reappear with an opposite character, exactly as it does in the chabasite under consideration."

SYSTEM IV.

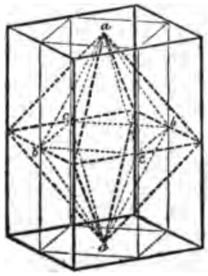
RIGHT PRISMATIC SYSTEM.

Synonymes.—The *right rhombic prismatic*, or *right rectangular prismatic system*, the *prismatic system*, the *two- and two-membered* or *one- and one-axed system*, the *orthotype system*, the *rhombic* or the *holohedric-rhombic system.*

Forms.—In this system are included the *right rhombic prism*, the *right rhombic octohedron*, the *right rectangular prism*, and the *right rectangular octohedron*. Rose enumerates the following forms as belonging to this system:

Homohedral.	*Hemihedral.*
1. Forms whose faces are inclined to all three axes (*Octohedra*).	Rhombic Tetrahedron.
2. Forms whose faces are inclined to two axes, but are parallel to the third (*Prisms*).	
3. Forms whose faces are inclined to one axis but are parallel to the two others (*Single Planes*).	

FIG. 39.



Right Rectangular Prism. | *Right Rectangular Octohedron.*
Right Rhombic Prism. | *Right Rhombic Octohedron.*
a. Principal or prismatic axis. *b b, c c.* Secondary axes.

Crystals.—The simple or elementary bodies which crystallize in forms belonging to this system are only three, namely, *iodine, native sulphur*, and *selenium.*

Among the binary compounds we have *pyrolusite* (binoxide of manganese), *white antimony* (sesquioxide of antimony), *bichloride of mercury, chloride of barium, orpiment*, and *grey antimony* (sesquisulphuret of antimony).

A considerable number of salts belong to this system, as the *carbonates of lead, baryta, strontian, potash*, and *ammonia;* the *bicarbonate of ammonia*, and that variety of carbonate of lime called *arragonite;* the *nitrates of potash, ammonia*, and *silver;* the *sulphates of magnesia, zinc, baryta*, and *strontian*, and *bisulphate of potash; Rochelle salt* (tartrate of potash and soda) and *emetic tartar* (tartrate of potash and antimony).

To the above must be added the following substances: *topaz, dichroite, citric acid* and *morphia.*

Properties.—The crystals of this system present the following properties: they have three rectangular axes all of different lengths: they are doubly refracting with two optic axes; and are tri-unequiexpanding. Consequently they have three rectangular unequal elasticities. On the ellipsoidal hypothesis, their atoms are ellipsoids, with three unequal axes.

They present no crystallographical character by which the *principal axis* can be distinguished from the others called *secondary axes;* so that in a geometrical point of view the choice of this axis is altogether arbitrary. But considered optically the principal axis is the middle point between the two nearest poles of no polarization. It corresponds with what is called by Mr. Brooke the *prismatic axis*; that is, the axis which passes through the centres of the terminal planes of the prism.

If you examine one of the simple or primary forms of this system—say this unmodified rectangular prism (the outer prism of figure 39), you observe there is no single line around which the figure is symmetrical; nor any square plane, or plane which can be inscribed within the circle. But let each of the two opposite terminal edges be replaced by a square plane, both equally inclined to the prismatic axis, and the line which passes through the centre of each of these planes will represent the direction of one of the optic axes.

As the crystals of this system have two optic axes, they present, when examined by the polariscope, a double system of rings. In nitre, carbonate of lead, and arragonite the inclination of these axes is small; and, therefore, both systems of rings may be seen at the same time.

In order to examine these by the polariscope, we must, in the case of the three crystals just mentioned, cut slices of them perpendicularly to the principal or prismatic axis. But in topaz, right prismatic mica, and Rochelle salt, the inclination of the optic axes is too great to permit both of them to be seen simultaneously; and, therefore, only one of them can be seen at a time. Consequently if we examine, by the polariscope, a plate of any of these crystals, cut at right angles to the prismatic axis, we must incline it first on one side and then on the other, to see successively the two systems of rings. To obviate this inconvenience, plates of these crystals should be prepared by grinding and polishing two parallel faces perpendicular to the axis of one system of rings.

Nitrate of potash, also called *nitre* or *saltpetre*, ($NO_5 + KO$) is a very instructive crystal for illustrating the double system of rings. It is usually met with in the form of a six-sided prism, with dïedral summits.

For placing in the polariscope, we use plates of from $\frac{1}{12}$th to $\frac{1}{15}$th of an inch in thickness, cut perpendicular to the prismatic axis. If one of these be put in the polariscope in such a position that the plane passing through the optic axis is in the plane of primitive polarization, we shall then perceive a double system of coloured elliptical or oval rings, intersected by a cross, but the centre of the cross is equidistant from the centres of the two systems of rings, so that through the centre of each system passes one arm or bar of the cross, the other arm being at right angles to the former. When the polarizing and analyzing plates are crossed, we have a double system of coloured rings, with a black cross (fig. 40); but when the polarizing and analyzing plates coincide, we have another double system of coloured rings, exactly complementary to the first, with a white cross (fig. 41).

FIG. 40.

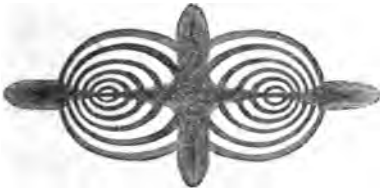
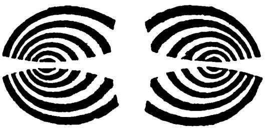


FIG. 41.



If when the analyzing and polarizing tourmaline plates are crossed, we revolve the plate of nitre in its own plane (both the tourmaline plates remaining unmoved) the black cross opens into two black hyperbolic curves. When the angle of rotation is a quarter of a right angle, we have the appearance represented by (fig. 42); when it equals half of a right angle, the black arms have assumed the forms of fig. 43.

FIG. 42.

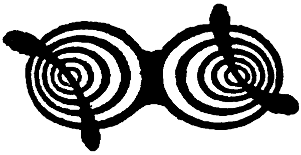
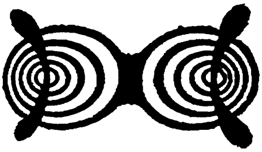


FIG. 43.



Here, then, is a remarkable distinction between biaxial and uniaxial crystals, for you will remember I demonstrated that when the uniaxial crystal was rotated in the polariscope, the black cross retained its position and shape.

The variation of form, as well as the general figure of the isochromatic lines, resembles the curve called by geometers the *lemniscate*. The inner rings encircle one pole only, but the outer ones surround both poles. The number of rings which surround both poles augments, as we diminish the thickness of the plate of nitre, until all the rings surround both poles, and the system thus greatly resembles, in appearance, the rings of an uniaxial crystal, from which, however, they are distinguished by their oval form.

I have already stated, that in biaxial crystals the optic axes for different colours do not coincide. In the case of nitre, the axes for red make with each other a smaller angle than the axes for blue. Hence the red ends of the rings are inward, that is, between or within the two optic axes, while the blue ends are outwards, or exterior to the two axes. But as the red rings are larger than the blue ones, it follows that there are points exterior to the axes where all the colours are mixed, or all are absent. At these spots, therefore, the rings are nearly white and black. Now if we trace the same rings to the positions between the axes, "the red rings will very much over-shoot the blue rings; and, therefore, the rings have the colour peculiar perhaps to a high order in Newton's scale[*]."

Native crystallized *carbonate of lead* constitutes a splendid polariscope object. It is to be cut like nitre; that is, perpendicularly to the prismatic axis. The optic axes are but slightly inclined (about 10½°) and, therefore, both of them may be simultaneously perceived. The systems of rings have a similar form to those of nitre, and like the latter, the red ends of the rings are inwards, the blue ends outwards.

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[*] Airy, *Mathematical Tracts*, p. 396. 2d ed. 1831.

Arragonite forms an interesting polariscope object. It is identical in chemical composition with calcareous or Iceland spar, but differs in crystalline form: calcareous spar belonging to the rhombohedric, arragonite to the right prismatic, system. According to Gustav Rose, both these forms of carbonate of lime may be artificially produced in the humid way, but calcareous spar at a lower, arragonite at a higher, temperature. In the dry way, however, calcareous spar alone can be formed.

The inclination of the optic axes of arragonite being small (about 18°) we can easily see, at the same time, the two negative systems of rings surrounding their two poles, but considerably more separated than in the case of nitre. For this purpose, a plate of the crystal is to be cut perpendicularly to the prismatic axis, that is, equally inclined (at about 9°) on each of the optic axes. If we rotate the plate of arragonite on its axis in the polariscope, the tourmaline plates being crossed and unmoved, the two sets of rings appear to revolve around each other. By superposing two plates of arragonite, we obtain four systems of rings.

In *Rochelle salt* (tartrate of potash and soda) the optic axes of the differently refrangible or coloured rays are considerably separated. If a plate of this crystal, cut perpendicularly to the prismatic axis, be inclined first on one side and then on the other, both the systems of rings may be successively perceived. But to observe the separation of the axes for differently coloured rays, Sir J. Herschel directs the plate to be cut perpendicularly to one of its optic axes. If we view the rings with homogeneous light they appear to have a perfect regularity of form, and to be remarkably well defined. With differently coloured lights, however, they not only differ in size but in position. If the light be "alternately altered from red to violet, and back again, the pole, with the rings about it, will also move backwards and forwards, vibrating, as it were, over a considerable space. If homogeneous rays of two colours be thrown at once on the lens, two sets of rings will be seen, having their centres more or less distant, and their magnitudes more or less different, according to the difference of refrangibility of the two species of light employed."

Topaz (a fluosilicate of alumina) belongs to this system. As the inclination of its optic axes is great (about 50°), we can see at once only one of its two system of rings. It slits with facility in planes perpendicular to its prismatic axis, and equally inclined to its two optic axes. If we take a plate cut perpendicularly to the prismatic axis, and incline it first on one side and then on the other, we shall see successively two systems of oval rings, which have been very elaborately described by Dr. Brewster.

The plates of topaz sold in the opticians' shops, for polariscope purposes, have been obtained by cutting the crystal perpendicularly to one of the optic axes; that is, at an angle of about 25° to the prismatic axis. With these we only see one system of nearly circular rings traversed by a bar or arm of the cross. We observe also, that the optic axes for different colours are somewhat separated; for the red ends of the rings are inwards, or within the resultant axes, while the blue ends are outwards.

The topazes, which are cut for optical purposes, come from Australia, and are technically known as *Nova Minas.* They are colourless and remarkably free from flaws and macles.

Exceptions.—In this system, as in the others, we meet with exceptions to some of the statements above made.

1. Macled crystals, especially of Nitre and Arragonite, are very common. Occasionally idiocyclophanous crystals of nitre are met with. These will be noticed subsequently.

2. *Sulphate of potash* is a tesselated or composite crystal, and as such will be described hereafter.

3. Some specimens of *Brazilian topaz* are tesselated.

SYSTEM V.

OBLIQUE PRISMATIC SYSTEM.

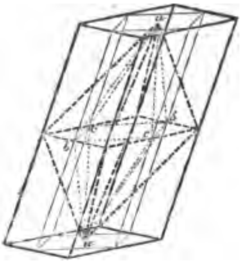
Synonymes.—The *two- and one-membered system*, the *hemiorthotype system*, the *monoklinohedric system*, or the *hemihedric-rhombic system.*

Forms.—To this system belong the *oblique octohedron with a rectangular base*, the *oblique rectangular prism*, the *oblique octohedron with a rhombic base*, and the *oblique rhombic prism.* Mr. Brooke's *right oblique-angled prism* is referred to this system.

Rose makes no distinction between the homohedral and hemihedral forms in this system; but enumerates the following as the forms of the system:

1. Forms whose faces are inclined to all the three axes (*Octohedra*).
2. Forms whose faces are inclined to two axes, and are parallel to the third axis (*Prisms*).
3. Forms of which the faces are inclined towards one axis and parallel to the two others.

FIG. 44.



Oblique Rectangular Prism, Oblique Rhombic Prism, Oblique Rectangular Octohedron, and Oblique Rhombic Octohedron.

a a. Principal axis. *b b*, *c c*. Secondary axes.

Crystals.—To this system belong the crystals of ***sulphur***, when obtained by slow cooling; ***realgar*** (red sulphuret of arsenic), and ***red antimony*** (native Kermes).

A considerable number of salts belong here also: as the ***sulphates of soda***, ***lime*** (selenite), and ***iron;*** ***carbonate*** and ***sesquicarbonate*** (trona) ***of soda***, ***bicarbonate of potash***, ***chlorate of potash***, ***phosphate of soda***, ***borax*** (tincal), the ***acetates of soda***, ***copper***, ***zinc***, and ***lead***, ***binacetate of copper***, ***binoxalate of potash***, ***glauberite*** (sulphate of lime and soda), and ***chromate of lead***.

To this system are also referred ***oblique prismatic mica*** (one of the kinds of diaxial mica described by Count de Bournon), ***tartaric*** and ***oxalic acids***, ***sugar candy***, and the ***crystals from oil of cubebs***.

Properties.—The forms of this system have three axes, all of which are unequal. Two of them cut one another obliquely, and are perpendicular to the third. From the forms of the preceding system they are distinguished by this obliquity of two of their axes. As the three axes are unequal, it is indifferent which we take for the ***principal axis;*** but one of the inclined axes is usually selected, because, in general, the crystals are extended in the direction of one of these, so that in most cases the faces which are parallel to this axis greatly predominate. This axis, therefore, corresponds with that which Mr. Brooke calls the ***prismatic axis***. The other two axes are called ***secondary axes***. the one which is oblique being termed the first secondary axis; the other, which is perpendicular to it, being denominated the second secondary axis.

The crystals of this system are doubly refracting with two optic axes. They are tri-unequiexpanding, and tri-unequiaxed. On the ellipsoidal hypothesis their atoms are assumed to be ellipsoids with three unequal axes.

In the opticians' shops, plates, cut from several crystals of the this system, are sold for showing, in the polariscope, the systems of lemniscates. They are usually cut perpendicularly to one of the optic axes; and, therefore, show but one system of rings traversed by a bar. Of these I shall notice three.

Borax deserves especial notice on account of its optic axes for the different homogeneous colours lying in different planes, a fact for the knowledge of which we are indebted to Sir John Herschel. As in other biaxial crystals it will be observed that the rings, or lemniscates, are traversed by only one bar or arm of the cross. In the next place it will be perceived, that the axes for red light make a greater angle with each other than the axes for blue or purple; hence, unlike nitre and carbonate of lead, the red ends of the rings are outwards, while the blue ends are inwards. This fact, however, only proves that the axes for different colours do not coincide: it does not show that they lie in different planes. But if, the tourmaline plates being crossed, the plate of borax be placed at such an azimuth that the bar or arm of the black cross distinctly traverses the centre of the system of lemniscates and leaves an interval perfectly obscure, we shall then see that the arm of the cross is not straight, as in nitre (fig. 40), but has a hyperbolic form. The reason of this difference is obvious: in nitre all the axes lie in the same straight line or plane, while in borax they are disposed obliquely, or in different planes.

Selenite is sometimes cut to show one of its two systems of rings. I have already described this crystal, and demonstrated the uniform tints produced by films of selenite of equal thickness. To show the rings the crystal must be cut at right angles to one of its optic axes.

Sugar Candy makes an interesting polariscope object. This crystal is also cut perpendicular to one of its optic axes, and, therefore, shows only one of its two systems of rings.

Exceptions.—Owing to irregularities of crystallization, the rings of some of the crystals of this system are often seen more or less distorted. Macled selenite is very common, as I have before mentioned. Sir John Herschel states, that idiocyclophonous crystals of *bicarbonate of potash* are frequent. I shall hereafter notice them.

SYSTEM VI.

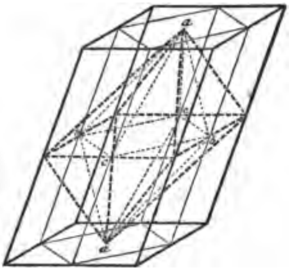
DOUBLY OBLIQUE PRISMATIC SYSTEM.

Synonymes.—The *one- and one-membered*, the *anorthotype*, the *triklinohedric*, or the *tetartohedric-rhombic system.*

Forms.—To this system belong the *doubly oblique octohedron* and the *doubly oblique prism.* Rose makes no distinction of homohedral and hemihedral forms; but arranges the forms of this system as follows:

1. Forms whose faces are inclined to all the three axes. (*Octohedra.*)
2. Forms whose faces are inclined to two axes, and are parallel to the third. (*Prisms.*)
3. Forms which have their faces inclined towards one axis only. These forms are the faces of truncation of the three kinds of angles of the octohedron.

FIG. 45.



Two Doubly Oblique Prisms, and two Doubly Oblique Octohedra.
a a. The Principal Axis. *b b, c c.* The Secondary axes.

Crystals —The most important substances, whose crystalline forms are referable to this system, are ***boracic acid, sulphate of copper*** [*], ***nitrate of bismuth, sulphate of cinchonia, quadroxalate of potash,*** and ***gallic acid.***

Properties.—The forms belonging to this system have three axes all unequal and oblique-angular to one another; they are doubly refracting, with two optic axes; and they are tri-unequiexpanding. Consequently they have three unequal elasticities.

Of the three axes just referred to, one is taken for the ***principal axis,*** the other two for the ***secondary axes;*** but geometrically considered the selection is altogether arbitrary. The principal axis coincides with Mr. Brooke's ***prismatic axis.***

"The forms of this system," says G. Rose, "have not symmetrical faces. All the faces are unique, so that this system is the one which differs the most from the regular or cubic system, in which we find the greatest symmetry on account of the equality and perpendicularity of the axes." It is sometimes exceedingly difficult to distinguish the forms of this system. "The doubly oblique prism," observes Mr. Brooke, "will be found the most difficult of all the primary forms to determine from its secondary crystals. It is distinguishable from all other forms, when its crystals are single, by the absence of symmetrical planes analogous to those of other prisms; but it very frequently occurs in hemitrope or twin crystals, which must resemble some of the forms of the oblique rhombic prism, and can then be distinguished only by some re-entering angle or other character on the surface of the crystal."

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[*] Mr. Brooke (art. *Mineralogy*, in the *Encyclopædia Metropolitana*), says, that the primary form of Sulphate of Copper is an oblique rhombic prism, and Mr. R. Phillips (*Translation of the Pharmacopœia*, p. 237, 4th edit., 1841) has adopted Mr. Brooke's statement. If this be correct, sulphate of copper of course belongs to the oblique prismatic system, and not to the doubly oblique prismatic system. I have, however, referred it to the latter system on the authority of Gustav Rose, and most of the other eminent German crystallographers.

Sulphate of Copper ($\mathrm{Cu\,O.\,S\,O_3.\,5\,Aq.}$) is sometimes cut to show the two sets of rings or lemniscates of this system; but the blue colour of the crystal destroys their brilliancy.

LECTURE IV.

4 CIRCULAR POLARIZATION.

The name of *circular* or *rotatory polarization* has been applied to a peculiar modification of light, first observed by Arago in the mineral called Quartz, and whose characteristic and distinctive properties I shall presently point out.

On the wave hypothesis, the term circular or rotatory is peculiarly appropriate, since it is assumed that the ethereal molecules describe circles, in other words that they vibrate or revolve uniformly in circles, and the form of the ethereal wave thereby produced, is that of a spiral or circular helix (that is, to a helix traced round a circular cylinder), of which a corkscrew and a bell-spring are familiar illustrations.

But apart from all hypothetical considerations, the name is an appropriate one. For unlike the rays of common polarized (that is, plane or rectilinearly-polarized) light, those of circularly polarized light have no distinction of sides, or, in other words, they have "no particular relations to certain regions of space," but present similar properties on all sides, and the angles of reflection at which they are restored to plane polarized light, in different azimuths, are all equal, like the radii of a circle described round the ray.

There are two varieties or kinds of circularly polarized light which have been respectively distinguished by the names of *dextrogyrate* or *right-handed*, and *lævogyrate* or *left-handed*.

In one of these the vibrations are formed in an opposite direction to those in the other. Unfortunately, however, writers are not agreed on the application of these terms; and thus the polarization, called, by Biot, right-handed, is termed, by Herschel, left-handed, and *vice versâ*. There is, however, no difference as to the facts, but merely as to their designation. If, on turning the analyzing prism or tourmaline *from left to right*, the colours descend in Newton's scale, that is, succeed each other in this order—*red, orange, yellow, green, blue, indigo, and violet*, Biot designates the polarization as *right-handed*, or +, or ↗; whereas if they descend in the scale by turning the analyzer *from right to left*, he terms it *left-handed*, or —, or ↘. Sir John Herschel, on the other hand, supposes the observer to look in the direction of the ray's motion. Let the reader, he observes, "take a common corkscrew, and holding it *with the head towards him*, let him use it in the usual manner, as if to penetrate a cork. The head will then turn the same way with the plane of polarization as a ray in its progress *from* the spectator through a *right-handed* crystal may be conceived to do. If the thread of the corkscrew were reversed, or what is termed a *left-handed thread*, then the motion of the head, as the instrument advanced, would represent that of the plane of polarization in a left-handed specimen of rock crystal."

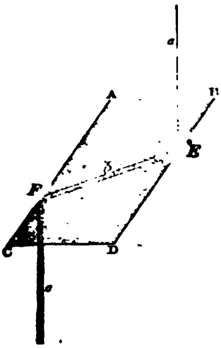
I shall adopt Biot's nomenclature, and designate the polarization right-handed or left-handed, according as we have to turn the analyzing prism to the right or to the left to obtain the colours in the descending order.

In a former lecture I endeavoured to explain the nature of circularly polarized light, according to the wave hypothesis. Powell's machine (see p. 27) gives a very clear notion of the difference between a circular and a plane wave. You may, perhaps, remember that I stated, that a circular wave is composed of two plane waves of equal intensity, polarized at right angles, and differing in their progress one quarter of an undulation. I endeavoured to demonstrate this fact by a machine invented, I believe, by Mr. Wheatstone (see p. 33).

Now, in order that you may comprehend how we effect the circular polarization of light, I must beg of you to keep in mind these statements. Remember, that to convert plane-polarized into circularly-polarized light, two conditions are necessary, namely, 1st, the existence of two systems of luminous waves, of equal intensity, polarized perpendicularly to each other; and, 2dly, a difference in the paths of these two systems of an odd or uneven number of quarter undulations. Now, whenever these two conditions are satisfied, circularly polarized light results. But how are we to satisfy them? By so doubly refracting plane polarized light, that the two resulting waves shall differ in their path an odd quarter undulation.

There are five modes of effecting the circular polarization of light, that is of satisfying the conditions above mentioned; but they all agree in acting on the principle now laid down, namely, that by them plane polarized light is doubly refracted, and two rectangularly polarized waves produced, which differ in their path an odd quarter undulation.

Fig. 46.



Fresnel's Rhomb.
A. B. C. D. Fresnel's Rhomb.
a. Incident ray of plane polarized light.
b. Depolarized ray.
c. Circularly polarized ray.

1. *Fresnel's Method.*—Fresnel effected the circular polarization of light by means of a parallelopiped of St. Gobin (crown) glass (fig. 46), whose acute angles, *B* and *C*, are about 54°, and consequently whose obtuse ones, *A* and *D*, are about 126°. This apparatus is commonly called *Fresnel's rhomb*. If a ray, *a*, of plane polarized light be incident perpendicularly on the face, *A B*, it will suffer two total internal reflections, at an angle of about 54°, one at *E*, the other at *F*, and will emerge perpendicularly from the face, *D C*. If the first plane, *B D*, of internal reflection, be inclined 45° to the plane of polarization of the incident ray, *a*, the emergent ray, *c*, will be circularly polarized.

Let us now endeavour to explain this phenomenon according to the wave hypothesis.

So long as reflection is *partial*, whether performed at the first or second surface of the diaphanous medium, the incident light suffers only a deviation from its plane of polarization, without having its primitive properties altered, whatever may be the azimuth of its plane relatively to that of the plane of reflection.

But when the reflection is *total* the case is very different. The reflected rays then have, in general, suffered partial depolarization, especially if the plane of reflection is in an azimuth of 45° relatively to the primitive plane of polarization. Now, a ray of light thus modified, or depolarized, as it is termed, may be represented by two rays polarized, the one according to the plane of reflection, the other perpendicularly to it. In other words, the incident-polarized ray (fig. 46, *a*) is resolved by reflection into two rectangularly plane-polarized rays (*b*), the planes of which are inclined respectively, the one 45° to the left, the other 45° to the right of the plane of polarization of the incident ray.

But it is obvious that the reflection of these two rectangularly polarized rays must be effected at different depths, and, therefore, under very different circumstances. The ray whose vibrations are performed parallel to the reflecting surface will glide, as it were, on the surface, and be reflected in a stratum of uniform density; whereas the ray, whose vibrations are performed perpendicularly to the reflecting surface, will penetrate to a greater depth, and pass into strata of varying density. The latter ray will, therefore, suffer a greater retardation than the one whose vibrations are performed parallel to the reflecting surface.

Now when, in the case of Fresnel's rhomb, the plane of the first reflecting surface is in an azimuth of 45° to that of the incident ray, the retardation is equal to ⅛th undulation. The same ray is farther retarded another ⅛th undulation by the second reflection; and now differs in its phase from that of the other ray ¼th of an undulation.

Thus are obtained the conditions necessary for the formation of a ray of circularly-polarized light; namely, two plane rays of equal intensity, polarized in planes perpendicular to each other, and differing in their path ¼th of an undulation.

2. *Airy's Method.*—If a ray of plane polarized light be transmitted through a lamina of either mica or selenite of such a thickness that, for a ray perpendicular to the lamina (that is, the ray polarized in the plane of one of the principal sections of the mica) the ordinary ray shall be retarded, an odd or uneven number of quarter undulations, as ¼th, ¾ths, or 5/4ths (according to the convenience of splitting) more than the extraordinary ray (that is, the ray polarized in the plane of the other principal section), the emergent light will be found to be circularly-polarized. In this case the incident light is resolved into two sets of vibrations, at right angles to each other, and one of these is retarded in its phases more than the other.

Between this and Fresnel's method of effecting circular polarization, there is this difference: in Fresnel's rhomb the retardation of the one ray is nearly the same for all colours, that is, for waves of different lengths. But in the case of the lamina of mica or selenite, the retardation is greater for blue rays than for red rays. "This is seen most distinctly on putting several such laminæ together [in the same crystalline position], when the light which is reflected from the analyzing plate is coloured, whereas, on putting together several of Fresnel's rhombs, there is no such colour. It is plain that in substituting such a lamina for Fresnel's rhomb, the plane of polarization of that ray which is least retarded, corresponds to the plane of reflection in the rhomb."

3. *Dove's Method.*—This consists in transmitting plane polarized light through glass to which a certain degree of doubly-refracting power has been communicated by pressure, or by rapidly heating or cooling it.

I have already shown that well annealed glass acquires doubly refracting properties when compressed; that unannealed glass possesses similar properties; and also that during the time that glass is rapidly heating or cooling it is likewise a double refractor.

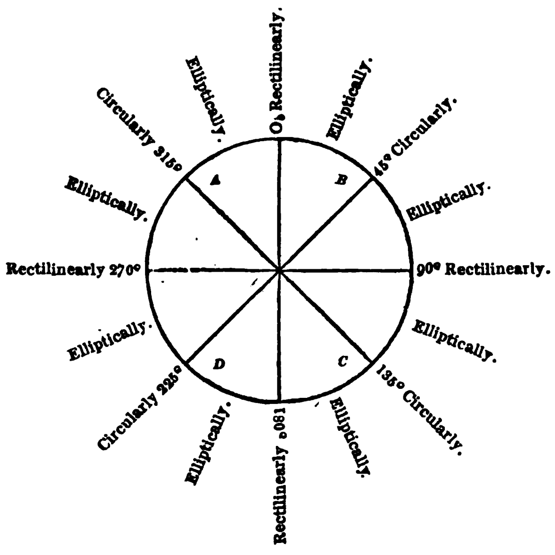
Of the two systems of waves which are thus obtained, one is polarized in a plane parallel to the axis of compression, the other in a plane perpendicular to it.

Now, if the degree of doubly refracting power thus communicated to glass be just sufficient to effect the retardation of one of the systems of waves ¼ of an undulation, we obtain a structure fitted for converting plane-polarized into circularly-polarized light.

"If a square or circular plate of glass," says Dove, "be compressed so that the axis of compression forms an angle of 45° or 135° with the plane of primitive polarization, the light passing through the centre of the glass at a certain degree of the pressure will be circularly polarized. During a complete revolution of the plate in its plane round the perpendicular incident ray as an axis of revolution, the light is polarized four times rectilinearly and four times circularly: rectilinearly when the compressing screw acts on the points 0°, 90°, 180°, 270°, that is to say, when the axis of compression is perpendicular to the plane of primitive polarization, or lies within it; and on the contrary, it is polarized circularly when that point of action corresponds to the points of division, 45°, 135°, 225°, 315°, whilst 45°, and 225°, as also 135°, and 315°, exhibit a similar effect."

These statements may be rendered more intelligible by the following diagram:

FIG. 47.



If light, rectilinearly polarized in the plane 0° 180°, or in that of 90° 270°, be incident on a circular disk of compressed glass (fig. 47, *A*, *B*, *C*, *D*), the emergent light is rectilinearly polarized when the axis of compression is either 0° 180°, or 90° 270°; but is circularly polarized when the axis of compression is either 45° 225°, or 135° 315°. At all intermediate azimuths it is elliptically polarized.

The degree of compression to which the glass is to be subjected, to produce these effects, is such that when the compressed glass is placed in the polariscope, with the tourmalines crossed, a black cross is seen with bloud-white vacant spaces in the corners.

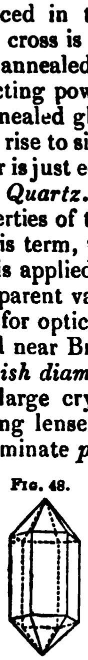
Unannealed glass, possessing the same degree of doubly refracting power, acts in a similar mannér to compressed glass.

Annealed glass, while either rapidly heating or cooling, likewise gives rise to similar effects at the time when its doubly refracting power is just equal to that of the compressed glass above described.

4. *Quartz.* — I now proceed to notice the remarkable optical properties of the substance denominated Quartz.

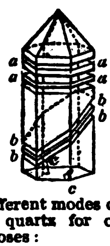
This term, the etymological origin of which is not clearly made out, is applied to some of the crystalline forms of silica. The transparent variety, called *rock* or *mountain crystal*, is the kind used for optical purposes. Very perfect transparent crystals are found near Bristol and in Cornwall, and are called *Bristol* or *Cornish diamonds*. The opticians cut some of the most limpid and large crystals, which usually come from the Brazils, for making lenses for spectacles and eye-glasses, and which they denominate *pebbles*.

FIG. 48.



Ordinary Crystal of Quartz.

FIG. 49.



Different modes of slitting quartz for optical purposes:

a a. Plates transverse to the prismatic axis, for shewing (in the polariscope) the system of circular rings (fig. 50).

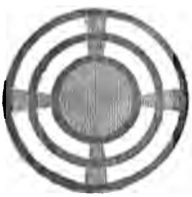
bb. Plates cut obliquely to the axis, for showing the straight bands.

c c. Wedges for making Wollaston's quartz doubly refracting prisms.

Quartz belongs to the rhombohedric system. Its most common form is the six-sided prism, terminated by six-sided pyramids (fig. 48). Its fracture is conchoidal.

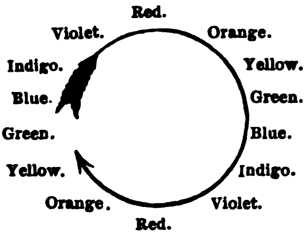
Now, as quartz belongs to the same system of crystals to which Iceland spar belongs, it might be expected that when we place a plate of it, cut perpendicularly to its principal or prismatic axis (fig. 49 *a a*), in the polariscope, we should observe the cross and a system of circular rings, as in the case of Iceland spar and other crystals of the rhombohedric system. But this is not the case. We do, indeed, observe a system of rings, but the centre of the cross is wanting (fig. 50). Instead of the cross within the inner ring we observe an uniform tint, the colour of which changes when the analyzer is revolved; and, in succession, all the colours of the spectrum are brought into view. But the order of succession (supposing the direction or revolution of the analyzer to remain the same) varies in different crystals. Thus, suppose we turn the analyzer right-handed, that is, as we screw up, the colours succeed each other, either in this order — *red*, *orange*, *yellow*, *green*, *blue*, *indigo*, *violet*, *red* again, and so on; or in the

Fig. 50.



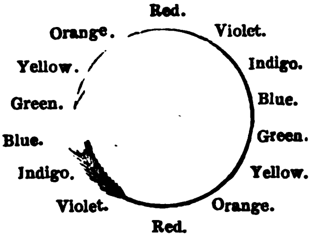
following order — *red*, *violet*, *indigo*, *blue*, *green*, *yellow*, *orange*, *red* again, and so on. So that to obtain the same order of succession, the analyser must be turned in the one case right-handed, or as we screw up, in the other left-handed, or as we unscrew. This will be rendered more obvious by the following diagrams:

Fig. 51.



Right-handed.

Fig. 52.

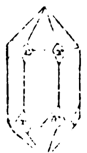


Left-handed.

In each of these diagrams the arrow shows the direction in which the analyzer is to be rotated, in order to obtain the spectral tints in the descending order. In one complete revolution of the analyzer each of the colours of the spectrum occurs twice. In other words, all the colours are seen in one semi-revolution of the analyzer.

Hence those specimens of quartz which present the colours in the descending order by a right-handed rotation of the analyzer, are denominated *dextrogyrate*, or *right-handed quartz;* while those which present them by a left-handed rotation are called *lævogyrate*, or *left-handed quartz*.

Fig. 53.



Plagiedral Quartz.

Between these two varieties there has been discovered by Sir John Herschel another difference. In that form of quartz, termed by Haüy *plagiedral* (from πλάγιος *oblique*, and ἕδρα *a base*), it has been found that when the unsymmetrical or plagiedral faces (fig. 53 *x*) lean to the right, the polarization is right-handed, and *vice versâ*, when they lean to the left the polarization is left-handed. So that the cause, whatever it may be, which determines the optical phenomena is also connected with the production of the plagiedral faces.

If, instead of using white light in our experiments, we employ homogeneous light, we find that the plane of polarization of the incident rays is turned or made to rotate either to the right or left, according as the quartz plate is either right-handed or left-handed. This rotation of the plane of polarization of the incident ray is proportional to the thickness of the plate. The rings produced by thin plates are broader and less numerous than those produced by thick plates. If two plates be superposed the effect is, very nearly, the same as that produced by a single plate whose thickness is either the *sum* or the *difference* of the thicknesses of the two plates; according as they are of the same kind (that is, both either right-handed or left-handed), or of opposite kinds (that is, one right-handed, the other left-handed). Thus, if the rotation of the red rays, effected by a plate of quartz of $\frac{1}{25}$th of an inch thick be equal to 17½°, that produced by two superposed plates of equal thickness, taken from the same crystal, will be $2\times 17\frac{1}{2}^\circ = 35^\circ$. On the other hand, if we combine a plate of right-handed quartz of $\frac{1}{25}$th of an inch thick with a plate of left-handed quartz of $\frac{4}{25}$ths of an inch thick, the same effects are produced as if we had employed a left-handed plate of $\frac{3}{25}$ths of an inch thick. When the thicknesses of the two dissimilar plates are equal "the plates of course destroy each other's effects, and the system of rings with the black cross will be distinctly seen." (*Brewster*).

The rotation of the plane of polarization increases with the refrangibility of the rays. Thus it is greater with violet than with blue, with blue than yellow, and with yellow than red.

Homogeneous Ray.	*Arc of Rotation.*
Extreme Red	17° 29′ 47″
Limit of Red and Orange	20° 28′ 47″
" Orange and Yellow	22° 18′ 49″
" Yellow and Green	25° 40′ 31″
" Green and Blue	30° 2′ 45″
" Blue and Indigo	34° 34′ 18″
" Indigo and Violet	37° 51′ 58″
" Extreme Violet	44° 4′ 58″

I come now to the explanation which the wave hypothesis offers of these phenomena.

When the light, rectilinearly polarized by the first tourmaline plate, is incident on the quartz plate, it suffers double refraction. To prove this, Fresnel contrived a combination of a right-handed prism, and two halves of a left-handed one, by which he doubled the separation of the two rays, and in this way managed to demonstrate the actual existence of double refraction in the principal or prismatic axis of quartz. This is a most remarkable fact. In the principal or prismatic axis of every other known crystal of the rhombohedric system double refraction does not exist.

But the two rays thus obtained differ in their properties from those produced by Iceland spar and other doubly refracting crystals, for while the latter are rectilinearly polarized, those of quartz are circularly polarized. Now every circularly polarized ray is equal to two rectilinearly polarized waves, differing in their progress an odd number of ¼ undulations. It follows therefore, that the two circularly polarized waves are equal to four rectilinearly polarized waves. Hence then to explain the phenomena, we must assume that the rectilinearly polarized ray (which I shall call *R*) incident on the quartz, is resolved into two others (*A* and *B*) of equal intensity, the one (*A*) polarized in a plane 45° inclined to the *right*, the other (*B*) 45° inclined to the *left* of the plane of polarization of the primitive ray (*R*). Let us further conceive that each of the two rays (*A* and *B*) is resolved into two other rays, namely *A* into *Aa* and *Ab*, and *B* into *Ba* and *Bb*. *Aa* and *Ab* are polarized in one plane, viz., + 45°, while *Ba* and *Bb* are polarized in another plane, viz.,—45°. *Aa* and *Ba* have each their phases advanced, or + ⅛ undulation, while *Ab* and *Bb* have each their phases retarded, or —⅛ undulation [*]. Now if we suppose these four rays to be combined two and two in a cross order, we shall have resulting two circularly polarized rays, one right-handed, the other left-handed. Thus *Aa* and *Bb* combine to form a left-handed ray, while *Ab* and *Ba* form a right-handed one. For when the advanced system of waves has its plane of polarization to the right of that of the retarded system, the ethereal molecules rotate from right to left; whereas they rotate from left to right when the first plane is to the left of the second.

These two circularly polarized rays are propagated along the axis of quartz with unequal velocities. In right-handed quartz, the right-handed ray is transmitted with greater velocity, in left-handed quartz with lesser velocity than the left-handed ray; and thus at their emergence one is in advance of the other. If the surface of egress or ingress be *oblique* to the axis, the two circularly polarized rays will emerge in different directions; but if it be *perpendicular* (as in the experiment under examination) they will emerge superposed, and will compound a single ray polarized in a single plane. Now this plane is removed from the plane of primitive polarization by an angle proportional to the interval of retardation (therefore, proportional to the thickness of the crystal) and to the refrangibility of the ray.

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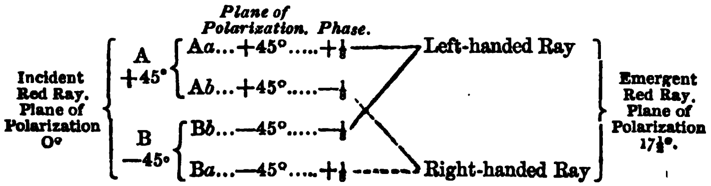
[*] "It results from the laws of interference," says Fresnel, "that a system of waves, polarized rectilinearly, may be replaced by two others, polarized at right angles to each other, and coinciding in their route; and that for each of these we may substitute two other systems of waves having the same plane of polarization, but the one advanced, the other retarded ⅛th of an undulation; and thus separated ¼th of an undulation. In this way are obtained four systems of waves of equal intensity, of which two, polarized at right angles to each other, are ¼th of an undulation behind the two others polarized in the same planes."

Thus then the differently coloured rays emerge from the quartz plate polarized in different planes; hence, by rotating the analyzer, they are successively transmitted and brought into view.

The following diagram may, perhaps, serve to render more intelligible the explanations of the action of a plate of quartz, of one millimetre (0.03937 of an English inch) in thickness, on the incident rectilinearly polarized red light.



A succession of quartz prisms does not give a further multiplication of images—a circumstance which distinguishes the double refraction of quartz from that of Iceland spar and other crystals.

The above explanation is applicable only when the direction of the rays *coincides* with the principal axis of the crystal. When it is *inclined* to this axis, Mr. Airy has shown that the two resulting rays are *elliptically polarized*, the elliptical vibrations in the two rays being in opposite directions (that is, one right-handed, the other left-handed), and the greater axis of the ellipse is for the extraordinary ray, in the principal plane of the crystal, and, for the ordinary ray, in a plane perpendicular to the principal one. The ratio of the axes in these ellipses, varies with the inclination of the ray to the principal axis of the crystal. When the direction of the ray coincides with this axis, the ratio is one of equality, and the ellipses become circles. But when the ray is inclined to the axis, the ratio increases indefinitely with the inclination. "It is also necessary to suppose that the axis of revolution of the spheroid (prolate for quartz) in which the extraordinary ray is supposed to diverge, is less than the radius of the sphere into which the ordinary wave diverges."

Hitherto we have had no satisfactory theory of the cause of the unequal velocities with which the two rays are transmitted along the principal axis of quartz. We conceive that it must depend either on some peculiarity in the molecules themselves, or in their mode of arrangement. "The crystal," says Fresnel, "cannot be constituted from right to left as it is from left to right, either in virtue of the arrangement of its particles, or of their individual constitution." If it be a molecular property, it must be acquired in the act of crystallization, by the mutual action of the molecules on each other, for other forms of silica, as well as melted quartz, are devoid of it. An helicoidal arrangement (right or left-handed, as the case may be) of the molecules furnishes a physical explanation of the fact above referred to. It has been objected to this hypothesis, that it is not applicable to the case of circularly polarizing liquids. But as the circular polarization of quartz is dependent on direction, while that of liquids is independent of it, it is tolerably clear that the cause must be different in the two cases. In the first, it may depend on the arrangement of the molecules; in the second, on some peculiarity in the molecules themselves.

If two plates of quartz, cut obliquely to the principal axis of the crystal (fig. 49, *b b*, *b b*), be superposed crosswise and examined in the polariscope, they present a series of parallel coloured bands or stripes, with a central black or white stripe. When the tourmaline plates are crossed, the central stripe is black, when they coincide, it is white. The lateral coloured stripes seen in the one case, are complementary to those seen in the other.

Amethyst is a mixture of right and left-handed quartz, and will be hereafter noticed among tesselated crystals.

5. *Circular Polarization by Fluids.*— Some liquids possess the remarkable property of circularly polarizing light. The following are the most important:

Volatile oils (those of mustard and bitter almonds excepted).
Naphtha.
Aqueous solutions of several kinds of *sugar*, *dextrine*, *tartaric acid*, and *tartrates* (tartrate of alumina excepted).
Diabetic urine.
Albuminous urine.
Alcoholic solutions of *camphor* and *artificial camphor.*
Most *vegetable juices.*

Biot found that vaporization did not destroy the circular polarization of oil of turpentine.

The following liquids have been found devoid of this property:

Water.
Alcohol.
Pyroxilic spirit.
Pyroacetic spirit.
Olive oil.

Volatile oil of mustard.
——————— *bitter almonds.*

Claret (perhaps a trace of ↘).

Champagne.
Citric acid (dissolved in water).
Mannite (ditto).
Liquorice sugar (ditto).
Glycerin.

The apparatus necessary for observing this property of fluids consists essentially of three parts; viz., a polarizer, a tube to contain the fluid, and an analyzer.

The *polarizer* is an unsilvered glass mirror, a bundle of parallel glass plates, or a Nichol's prism. Both Biot and Professor Powell use the first, while Ventzke employs the last. A plate of glass, blackened at the posterior surface, answers very well. Sometimes a second mirror (of silvered glass) is used to throw the light on the polarizing plate.

The *tube*, to hold the liquid, should be from six to twenty-four inches long. In general, it is to be filled with the fluid under examination, and to be closed at each end by a flat glass plate. Professor Powell, however, employs a common test-tube, open at the top, and having the usual hemispherical bottom. In some cases it is desirable to have two or three perforated diaphragms of sheet silver or platinum, placed at intervals in the tube, to exclude the light reflected from the sides of the tube, but to admit those rays which traverse the axis of the tube.

The *analyzer* should be either an achromatic, doubly refracting prism, or a Nichol's prism. Biot uses a doubly refracting prism of calc spar, made of a rhombohedron of this substance, rendered achromatic by replacing a portion of the crystal by a glass prism. Achromatic quartz prisms are objectionable, since they are never so accurately prepared as to yield two images only, but always four; of which two, however, are very faint. Professor Powell employs a rhombohedron of calc spar, in its natural state, as his analyzer, and a lens to magnify the separation of the images. Ventzke uses a Nichol's prism as the analyzer.

The amount of rotation which a ray of light suffers during its passage through the liquid, is measured by an index attached to the analyzer, and moving on a graduated circular metallic plate. Before the tube containing the liquid is introduced, we must fix the zero, or 0°. If a doubly refracting prism be the analyzer, the index is made to point to zero, or 0°, when the ordinary image alone is seen. If, however, a Nichol's prism be used as analyzer, the index is arranged to point to O° when the light is excluded; or, in other words, when the light, transmitted by the polarizer, is extinguished by the analyzer.

Homogeneous light is generally employed when we wish to measure the arc of rotation affected by a liquid on a luminous ray. Red light is usually selected, because this is the only homogeneous light which can be isolated by coloured glass. We, therefore, place a plate of red glass between the eye and the analyzer.

If, when the index points to zero O°, the tube containing a circularly polarizing liquid be introduced, the second or extraordinary image immediately becomes evident, if the doubly refracting prism be used as analyzer. By turning the latter round to the right or to the left, as the case may be, this second image disappears (when homogeneous light is used), and the arc traversed by the index from the zero O°, measures the angle of deviation of the ray. If, however, a Nichol's prism be employed, it no longer excludes the light when the index stands at O°, but requires to be rotated a certain number of degrees to do so, and the arc of rotation is here a measure of the rotative power of the liquid.

The explanation of the action of these liquids on the incident rectilinearly polarized light is similar to that already given for the axis of quartz; with the exception, that in the case of quartz, the circular double refraction may depend on the arrangement of the molecules, whereas in liquids it must arise from some property of the molecules themselves.

I proceed now to examine some of the liquids which possess the property of circular polarization:

First, with regard to the *essential* or *volatile oils.* Most of these bodies are circular polarizers: indeed, I know but two exceptions to this statement, viz. oil of mustard and oil of bitter almonds. Some turn the planes of polarization to the right, others to the left, but the intensity of their rotative power varies considerably, as the following table shows:

CIRCULAR POLARIZATION OF THE VOLATILE OILS.

1. *Left-handed*, or *Lævogyrate.*

	Arc of Rotation with the Red Rays through a thickness of 200 *Millimetres.*
Oil of Turpentine	59° 21′
" Mint	32° 28′
" Anise	1° 52′
" Rue	?
Naphtha	15° 21′

2. *Right-handed*, or *Dextrogyrate*

Oil of Lemon	110° 53′
“ Bergamot	38° 16′
“ Bigarade	157° 89′
“ Citron	—
“ Limette	—
“ Neroli	—
“ Fennel	26° 32′
“ Caraway	131° 58′
“ Lavender	4° 04′
“ Rosemary	6° 58′
“ Knotted Marjorum	23° 68′
“ Sassafras	7° 06′
“ Savine	14° 12′

This table is a very instructive one. It shows that isomerism has no connection with circular polarization, for of three isomeric oils (turpentine, lemon, and bergamot) mentioned in this table, one is lævogyrate, the others dextrogyrate. We see also, that oils derived from plants of the same natural family (as the oils of anise, fennel, and caraway from the *umbelliferæ*, and those of mint, lavender, and rosemary from the *labiatæ*) differ in respect of their circular polarization. In some cases, perhaps, this fact might be available to the Pharmaceutical Chemist in detecting mixtures of one oil with another, as the adulteration of oil of peppermint with oil of rosemary, recently mentioned by Mr. Herring. (See *Pharmaceutical Journal*, vol. i., p. 263).

Some kinds of *sugar*, when dissolved in water, yield solutions which have in a greater or less degree the property of rotating the planes of polarization, some to the right, others to the left. Hence polarized light may be sometimes used as a test of the presence of sugar, and the degree of rotation becomes an indication of the quantity and even quality of the sugar present. Biot examined by this test a specimen of sugar-cane juice, and found that it indicated the presence of 20 or 21 per cent. of sugar. Peligot subsequently analyzed it, and found 20.9 per cent. of sugar. Biot, therefore, suggests that those who make, as well as those who refine sugar, might resort to this test as a means of determining the amount of sugar in different juices or solutions. To the colonist it would prove useful by pointing out the saccharine strength of the juice at the mill, and to the sugar refiner it would be valuable by enabling him to determine the absolute strength of raw sugar.

The sugars are prepared for examination by dissolving them in water, and decolorizing the solutions when necessary, by filtering them through purified granulated animal charcoal.

Several sweet or saccharine substances do not indicate any circular polarization, and of those that do, some indicate right-handed, others left-handed circular polarization.

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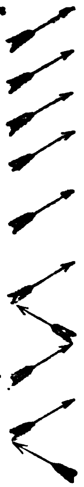
1. Cane Sugar		*Right handed.*
2. Grape Sugar (*Glucose* of Dumas)		*ditto*
3. Incrystallizable Sugar (*Chulariose* of Soubeiran)	a. Incrystallizable Sugar of Honey	*Left handed.*
	b. Incrystallizable Sugar, obtained by the action of acids on Cane Sugar	*ditto.*
	c. Incrystallizable Sugar of the juices of Fruits	*ditto*
	d. Incrystallizable Sugar, obtained by the alteration of Cane Sugar. This constitutes the greater part of Molasses	*ditto.*
4. Mannite		0
5. Glycerin		0
6. Liquorice Sugar		0

The grape sugar referred to in this table exists ready formed in honey, and in diabetic urine. It is deposited when the acidulous juices of fruits have been saturated and sufficiently concentrated. Moreover, it is produced by the action of diastase on starch, as well as when syrup, obtained by the action of weak acids on starch or sugar, is abandoned to itself.

The following table, taken from a memoir, by Biot, shows the extent of rotatory power possessed by different sugars:

ROTATION OBSERVED WITH RED GLASS THROUGH A SOLUTION OF 152 MILLIMETRES IN LENGTH.

	Proportion of Sugar in one of the solution.	*Arc of Rotation*
Sugar Candy 1. Aqueous solution	0.25	23° 28′ 45″
" 2. "	0.50	51° 28′ 45″
" 3. "	0.65	70° 11′ 15″
Cane Sugar syrup, boiled, and rapidly cooled	0.244	16° 50′ 33″
Sugar of Milk, crystallized (aqueous solution)	0.14	10° 21′ 40″
Starch Sugar, white grains (ditto)	0.648	48° 30′ 0″
Grape Sugar syrup	—	— — —
" in white grains (aqueous solution)	0.1558	— — —
Crystallizable principle of Honey	0.34201	16° 47′ 30″
Uncrystallizable ditto	—	— — —



Cane sugar, dissolved in water, causes *right*-handed polarization. A strong syrup made with refined sugar shows the colours most brilliantly. When this kind of sugar is subjected to heat, especially in contact with acids, it loses its crystallizability, and then acquires *left*-handed polarization. In the manufacture of barley-sugar, hardbake, &c., the makers of these kinds of hard confectionary use a little cream of tartar to destroy the crystallizability of sugar. Soubeiran found that a syrup of cane-sugar heated by a salt-water bath, the air being excluded, underwent a series of remarkable changes in respect of its rotative power.

	Arc of Rotation for mean Yellow Ray for a length of 100 *Millimetres.*	
Syrup, primitive	+71	↗
" After twenty hours	0	
" After twenty-five hours	−11	↖
" After sixty-four hours	0	
" After seventy-two hours	+ 5	↗

Here then it appears, that cane-sugar ↗ gradually lost its rotative power 0°, and then became ↖. In this latter state it was probably incrystallizable sugar. But this in its turn lost its rotative power 0°, and became ↗. The precise nature of the latter kind of sugar is not known.

In sugar-refining the object is never to let the syrup get beyond the first zero; that is, not to convert crystallizable unto uncrystallizable sugar. Raw sugar contains, however, both crystallizable and uncrystallizable sugar: the latter alone should constitute treacle. But, from Soubeiran's optical examination, it appears that treacle contains a portion of crystallizable sugar.

The optical characters of sugar have been made use of to detect fraud in Pharmacy. In 1842, more than a ton of a substance purporting to be *manna* was offered for sale in Paris at less than fivepence per pound, the excuse given for the unusually low price was, that cash was immediately required. Suspicion was raised, and the substance was submitted to careful examination, the result of which was the establishment of the fact, that it was not manna, but potato-sugar. Its aspect, taste, fermentibility (mannite not being fermentible), and the presence of sulphate of lime proved this. Biot submitted it to a very careful optical examination, and found its characters to be those of a starch-sugar. Manna contains two kinds of saccharine matter, one called *mannite,* and the other a *fermentable sugar.* Now mannite, when pure, has no rotative power on polarized light, but commercial manna has a slight effect, owing to the presence of a small quantity of fermentable sugar. This fictitious substance, however, had the same effect on plane polarized light, as sugar prepared by the action of acids on starch, when the action is arrested at the first phase of its transformation.

Vinous fermentation has been studied by the aid of polarized light. Take a solution of cane-sugar which has *right-handed* circular polarization. As soon as it begins to ferment it loses this property, but acquires *left-handed* polarization.

Polarized light has been prepared and used as a test of the presence of sugar in urine. To render diabetic urine available for this purpose, it must be decolorized by agitation with fresh prepared granulated animal charcoal, and subsequent filtration. The process is troublesome, tedious, and can only prove successful in the hands of persons familiar with the phenomena of polarized light. With all due deference to Biot, I do not think it will ever prove of much value in practical medicine. We have other, simpler, less laborious, and cheaper methods of detecting sugar in urine than the one now referred to. Moreover, it should be remembered, that albuminous urine possesses the property of circular polarization.

The substance called *dextrine* is starch-gum, and is soluble in water. It is usually prepared from potato-starch, either by torrefaction or by the action of a small quantity of nitric acid. A solution of it possesses the property of right-handed circular polarization, hence the name *dextrine* applied to it by Payen and Persoz.

Properties of circularly polarized Light.—Common, rectilinearly polarized, and circularly polarized, lights are undistinguishable by the eye. All three may be coloured or white. The properties which distinguish the latter from the two former are as follows:

1. A ray of circularly polarized light is capable of reflection by a reflecting plane, as of glass, in every azimuth of the plane of reflection. For the circular vibrations of the ethereal molecules may be resolved into two equal rectilinear vibrations, one parallel, the other perpendicular, to any arbitrary plane.

By this property, therefore, circularly polarized light differs from rectilinearly polarized light, but agrees with unpolarized light.

2. A ray of circularly polarized light is capable of transmission through a plate of tourmaline (cut parallel to the axis of the crystal), in every azimuth of the axis of the crystal. For in this case also, the circular vibrations of the incident ray may be resolved into two equal rectilinearly vibrations, one parallel, the other perpendicular, to any azimuth. One of these vibrations is transmitted by the tourmaline, the other is suppressed.

In this property also circularly polarized light agrees with common or unpolarized light, but differs from rectilinearly polarized light.

3. Analyzed by a doubly refracting prism of Iceland spar, a ray of circularly polarized light gives constantly two equal images, in whatever plane the principal section of the prism be placed. For, as I have already stated, a ray of circularly polarized light is the resultant of two rays placed at right angles and differing in their phase by a quarter undulation; and, therefore, it must give equal images by the doubly refracting prism, in the same way that common or unpolarized light does, for the difference of phases has nothing to do with this character.

In this respect circularly polarized light agrees with common or unpolarized light; but is distinguished from rectilinearly (plane) polarized light, which in certain positions (before specified) yields one image only.

4. By two total internal reflections in the interior of glass, at an angle of about 54½°, circularly polarized light is converted into rectilinearly polarized light. Thus if light circularly polarized be incident on Fresnel's rhomb, it emerges rectilinearly polarized, and the position of the plane of polarization at emergence makes an angle of +45° or —45°, with the plane of reflection according as the incident light was right-handed or left-handed. This experiment may be readily understood from the explanation already given of the action of Fresnel's rhomb in converting rectilinearly polarized light into circularly polarized light (fig. 46, p. 88). In fact, the two experiments are the converse of each other; the light called *incident* in the one case, being termed *emergent* in the other, and *vice versâ*.

In this character, circularly polarized light differs equally from both unpolarized and rectilinearly polarized lights. For by two reflections of this kind, common light suffers no obvious change; while rectilinearly polarized light, under the same circumstances, is converted into circularly polarized light, provided that the plane of reflection be at an azimuth of 45° to that of primitive polarization.

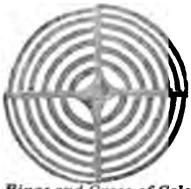
5. If a ray of circularly polarized light be transmitted through a thin film of a doubly refracting crystal, and the emergent light be analyzed by a doubly refracting prism, two rays of complementary colours are produced.

In this character, circularly polarized light is decidedly different to common or unpolarized light, which when submitted to the same examination presents no colour. Rectilinearly polarized light, however, agrees with the circular light in producing complementary tints; but they are not the same in the two cases; those produced by circular light differing from those of rectilinear light by an exact quarter of a tint, either in excess or defect, as the case may be.

To illustrate these facts, place a film of selenite, of uniform thickness, in the polariscope, and observe the tint which it yields by rectilinearly polarized light. Then interpose, between the polarizing plate and the selenite film, a circularly polarizing apparatus (as Airy's mica plate, or Fresnel's rhomb), and the tint seen by the analyzer immediately changes.

If a plate of calcareous spar, cut to show the circular rings and cross by rectilinearly polarized light, be placed in the polariscope, and circularly polarized light be used, we observe a system of rings and a cross (fig. 53), but which are very different to those seen by rectilinearly polarized light.

FIG 53.



Rings and Cross of Calc Spar produced by circularly polarized light.

The rings are divided into quadrants by the cross, every other quadrant being similar, while the adjacent ones are dissimilar. The rings appear to be abruptly and absolutely dislocated, those in the two alternate quadrants being pushed outwards or from the centre, by ¼ of an order, and those of the intermediate quadrants being as it were pulled inwards by ¼ of an order. Instead of a black cross, we have a luminous one, the intensity of its light being uniform, and about equal to the mean intensity. If the plane of incidence pass through 135° and 315°, the phenomena of adjacent quadrants are exactly interchanged. But the most important difference produced by circularly polarized light, is, that no alteration is made by turning the analyzing plate round the incident ray.

If a plate of a biaxial crystal, as of nitre, be examined by circularly polarized light, we observe the double system of rings, but the black cross disappears. Every alternate semicircle of rings presents the appearance of dislocation.

The origin of the tints produced by circularly polarized light, have been so clearly and concisely explained by Sir John Herschel, that I cannot do better than use his words:

"When," says this eminent philosopher, "a ray propagated by circular vibrations is incident on a crystallized lamina, it may be regarded as composed of two; one polarized in the plane of the principal section, the other at right angles to it, of equal intensity, and differing in phase by a quarter undulation. Each of these will be transmitted unaltered; and, therefore, at their emergence, and subsequent analysis, will comport themselves in respect of their interferences, just as would do the two portions of a ray primitively polarized in azimuth 45°, and divided into two by the double refraction of the lamina; provided that a quarter undulation be added to the phase of one of these latter rays. Now, such rays will produce, by the interference of their doubly refracted positions, the ordinary and extraordinary tints due to the interval of retardation within the crystallized lamina. Hence, in the present case, the tints produced will be those due to that interval, *plus* or *minus* the quarter of an undulation added to, or subtracted from, the phase of one of the portions; and, consequently, will differ one-fourth of a tint in order from that which would arise from the use of a beam of ordinary polarized light, incident in azimuth 45° in the lamina."

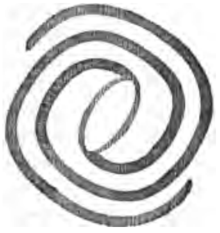
§ 6. If a ray of circularly-polarized light be transmitted through a column of syrup or oil of turpentine, lemon, &c., and then analyzed, either by a Nichol's prism, or a doubly-refracting prism, no colour is produced. For the circular wave is propagated along the liquid without suffering subdivision, and, therefore, at its emergence, no colour can be produced by the analyzer.

In this character circularly-polarized light agrees with common or unpolarized light; but differs from plane polarized light.

7. "Circularly-polarized light," says Fresnel, "differs from plane polarized light in not sensibly developing colours in plates of quartz perpendicular to the axis." According to the wave hypothesis this ought to be the case; for "a ray propagated by circular vibrations, when incident on rock crystal in the direction of the axis, will (by hypothesis) be propagated along it by that elasticity which is due to the direction of its rotation, the wave then will enter the crystal without further subdivision, and there will be no difference of paths or interfering rays at its emergence; and, of course, no colours produced on analyzing by double refraction."

I confess, however, I have not been able precisely to verify this statement, though, I doubt not, my failure has arisen from some defect in the apparatus used to produce circular polarization. I have always found a very feeble tint of colour in the axis. As Mr. Airy has very accurately described the phenomena which I myself have repeatedly seen, I prefer quoting his words:

FIG. 54.



Spirals of Quartz, produced by circularly-polarized light.

"If circularly-polarized light pass through the quartz, on applying the analyzing plate, instead of rings, there are seen two spirals mutually enwrapping each other [as in fig. 54.]. If the [Fresnel's] rhomb be placed in position 135°, the figure is turned through a quadrant. If the quartz be left-handed, the spirals are turned in the opposite direction. The central tint appears to be white. With the rhomb which I have commonly used (which is of plate-glass, but with the angles given by Fresnel for crown-glass), there is at the centre an extremely dilute tint of pink: I think it likely that this arises from the error in the angles, as the intensity of the colour bears no proportion to that in other parts of the spiral."

If a plate of right-handed quartz be superposed on a plate of left-handed quartz of equal thickness, and examined by circularly-polarized light, the left-handed slice being nearer to the polarizing plate, we observe, by means of the analyzer, four spirals (proceeding from a black cross in the centre) which cut a series of circles at every quadrant. At some distance from the centre the black brushes are seen. If the right-handed slice be nearer the polarizing plate, the spirals are turned in the opposite directions.

8. Mr. Earnshaw inferred, theoretically, from Fresnel's formulæ, that if right-handed circularly-polarized light be incident nearly perpendicularly upon a plane surface of glass, the reflected light will be left-handed circularly-polarized, and *vice versâ.* The Rev. Professor Powell has subsequently verified experimentally Mr. Earnshaw's theoretical deduction.

Airy's analyzer for Circularly-Polarized Light.—I have already stated and described two kinds of circularly-polarized light; the one called right-handed, the other left-handed. To distinguish them, Mr. Airy contrived an analyzer which suppresses one and transmits the other. "It is well known," he observes, "that if circularly-polarized light is incident on Fresnel's rhomb, it emerges plane-polarized, and the position of the plane of polarization at emergence makes an angle of +45°, or —45° with the plane of reflection, according as the incident light was right-handed or left-handed. Let the light emerging from the rhomb be received on an unsilvered glass at the polarizing angle, whose plane of reflection makes the angle +45° with that of the rhomb. Now it is plain that if the light incident on the rhomb was right-handed, it becomes plane-polarized in the plane of reflection of the glass, and, therefore, is wholly reflected; if it was left-handed, it becomes plane-polarized in the plane perpendicular to the plane of reflection of the glass, and, therefore, is wholly suppressed." It is then obvious, that this combination of Fresnel's rhomb and on unsilvered glass at +45°, or —45°, would form an analyzer for circularly-polarized light. But as Fresnel's rhomb is inconvenient, on account of its length, Mr. Airy has substituted "a plate of mica of such a thickness that the ray polarized in the plane of one of its principal sections is retarded either $\frac{1}{4}$th, $\frac{3}{4}$ths, or $\frac{5}{4}$ths of a wave (according to the convenience of splitting) more than that polarized in the plane of the other. The mica being attached to the unsilvered glass, so that its principal section makes an angle of 45° with the plane of reflection, an analyzer is produced, which answers the same purposes, in general, as that described above."

6. ON ELLIPTICAL POLARIZATION.

Time will permit to say a few words only respecting elliptically polarized light.

If two systems of waves of equal intensity, polarized rectangularly to each other, differ in their progress a fractional number of ¼ undulation, the vibratory movements of the ethereal molecules will be neither rectilinear nor circular, but elliptical. The waves formed by such vibrations will be elliptical, and may be compared to an elliptical helix (that is, to a helix traced round an elliptical cylinder), right-handed or left-handed, as the case may be.

Powell's machine gives a very good idea of elliptical vibrations and elliptical waves.

The manner in which two rectangularly polarized waves interfere and produce elliptical waves, is shown by Wheatstone's apparatus.

There are several modes of effecting the elliptical polarization of light. If in the experiments with Fresnel's rhomb (see *Circular Polarization)* the planes of polarization and incidence be at any other angle than 45° the emergent ray will be elliptically polarized.

Airy's mode of producing circular polarization may be used to obtain elliptical light; but the mica plate, through which the ray is perpendicularly transmitted, must be placed at an azimuth between that which yields circularly polarized, and that which admits plane polarized light.

Compressed, or unannealed glass, also yields elliptically polarized light, under conditions which I have explained when describing Dove's method of circular polarization.

Quartz also produces elliptical polarization when the direction of the incident ray is inclined to the axis.

By reflection from metallic surfaces light becomes elliptically polarized. The elliptical light reflected from silver is nearly circular, while that from galena is almost plane: that is, the ellipsis in the one case is nearly a circle, in the other nearly a straight line.

Elliptically polarized light is not distinguishable, by the eye, from other kinds of light. If it be analyzed by a Nichol's prism, an unsilvered glass mirror, or a plate of tourmaline, it never vanishes during the revolution of the analyzer. By this it may be known from rectilinearly polarized light. But at different azimuths of the analyzer the intensity of the light varies; and by this it may be known from both unpolarized and circularly polarized light. If it be analyzed by a rhombohedron of calc spar, it gives two images in all positions of the analyzer. In this respect it differs from plane polarized light. But one of the images exhibits a defalcation of light, showing that the incident light is not common or unpolarized. If elliptically polarized light be transmitted through an uniaxial crystal (as

Iceland spar) cut perpendicularly to its axis, and the emergent light be afterwards analyzed, it presents a system of rings and cross different to those obtained from either plane or circularly polarized light.

The preceding are some only of the peculiarities which distinguish this from other kinds of light; and in conclusion, I may observe, that elliptical polarization forms a connecting link between plane and circular polarization.

5. MACLES AND COMPOUND CRYSTALS.

I have now arrived at the last part of my subject, viz., the consideration of the optical properties of those remarkable crystalline structures commonly known by the name of *macles*, a term introduced into mineralogy by Romé de Lisle. Sometimes these structures appear to consist of one crystal, whose parts are transposed, dislocated, or displaced. When one-half of the crystal appears to have been turned partly round on an imaginary axis, passing through the centre of the crystal, and perpendicularly to the plane of section, and to have been united to the other half in this position, the body thus produced has been called the *hemitrope* (from ἡμι *half* and τρέπω *I turn*). Of this arrow-headed selenite is a familiar example. Sometimes two or more crystals are found intersecting each other, and are then called *intersecting crystals.* When two crystals are joined, they form the structure called a *twin* or *double crystal.*

Many or most of the forms I have now referred to are irregular, and might appear to be accidental. But there are some others which have great regularity, and cannot be ascribed to accident. Such are some specimens of apophyllite and sulphate of potash. They constitute what Dr. Brewster has termed *tesselated* or *composite crystals;* the real structure of many of which is only discoverable by the aid of polarized light; they consist of several crystals, or portions of crystals, juxtaposed, or united so as to form a compound crystal, the figure of which is very different from that of the crystals composing it.

Macled crystals of *nitre* and *arragonite* are very common, and frequently their precise structure is undiscoverable by the naked eye.

In *quartz* we often find right and left-handed crystals intersecting each other.

Amethyst (by many mineralogists considered to be a variety of quartz), is a remarkable example of a combination of right and left-handed varieties of quartz. If a plate of amethyst, cut perpendicularly to the principal axis of the crystal, be examined by the polariscope, it presents a striped or fringed appearance, variegated with the most gorgeous and brilliant tints. This is owing to its being composed of alternate minute strata of right and left-handed quartz, whose planes of polarization are parallel to the principal axis of the prism.

Topaz sometimes presents a remarkably composite structure. It belongs to the right rhombic system, and presents, when regularly formed, two systems of rings. Cut at right angles to the axis it often presents a central rhomb, "surrounded by a border in which the optic meridians of the alternate sides are inclined at a quarter of a right angle to that of the central compartment, and half of a right angle to each other. In consequence, when such a rhombic plate is held with its long diagonal in the plane of primitive polarization, two opposite sides of the border appear bright, the other two black, and the central compartment of intermediate brightness. Such specimens often present the phenomena of dichroism in the central compartment, while the border is colourless in all positions*."

Sulphate of potash is composed of six crystals belonging to the right prismatic system, joined so as to form a single or double six-sided pyramid, and simulating the crystals of the rhombohedric system. When, therefore, we put a slice of it, cut at right angles, to the axis of the pyramid, in the polariscope, we observe not a circular cross and rings, but a tesselated structure.

One variety of *apophyllite*, called *tesselite*, presents a remarkable structure of the same kind; but its phenomena are still more extraordinary. Apophyllite is composed principally of silicate of lime, with a little silicate of potash. It crystallizes in right square prisms. Plates cut transversely to the axis, and examined by polarized light, appear to consist of nine crystals contained within a number of parallel veins or plates. The central crystal has only one axis of no double refraction, the others two. (See p. 68).

Analcime or *Cubizite* is another remarkable crystal. It consists principally of silicate of alumina with silicate of soda. It crystallizes in the form of the cube, or some form allied to this, as the icosatetrahedron. Instead of being without double refraction, as cubical crystals usually are, it presents a number of planes of no double refraction. It is, therefore, a compound crystal, that is, is composed of a number of crystalline parts disposed symmetrically. (See p. 66).

And here also may be noticed what has been called *interrupted Iceland spar.* Some specimens of Iceland spar give four or even more images, which sometimes exhibit complementary tints. They owe this property to the presence of one or more intersecting or interrupting films or strata of the same substance, placed perpendicularly to the short diagonal of the faces of the crystal. This film acts like the depolarizing plate in the polariscope, while the two portions of the crystal between which it is placed, act, the one as the polarizer, the other as the analyzer of the polariscope. Crystals like these, which thus exhibit their colours and rings *per se*, that is without the polariscope, have been called by Sir John Herschel, ***idiocyclophanous*** (from *ἴδιος proper*, *κύκλος a circle*, and *φαίνω I appear*). Similar phenomena are sometimes exhibited by crystals of ***nitre***, and still more frequently by ***bicarbonate of potash***.

---

* Herschel, *Encycl. Metrop.*

Conclusion.—The lateness of the hour compels me to avoid any lengthened peroration. I shall, therefore, content myself with thanking my auditors for the great attention which they have manifested during the entire course.

THE END.

C. WHITING, BEAUFORT HOUSE, STRAND.

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